THE INFLUENCE OF TERMINATION CONFIGURATION ON THE FLOW PERFORMANCE OF FLUES

A Study Prepared for

CANADA MORTGAGE AND HOUSING CORPORATION

by

Scanada Consultants Limited

Scanada Sheltair Consortium Inc.

June 11, 1987

Canada Mortgage and Housing Corporation, the Federal Government's housing agency, is responsible for administering the National Housing Act.

This legislation is designed to aid in the improvement of housing and living conditions in Canada. As a result, the Corporation has interests in all aspects of housing and urban growth and development.

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This publication is one of the many items of information published by CMHC with the assistance of federal funds.

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June 11, 1987

This project was funded by the Canada Mortgage and Housing Corporation and Energy, Mines and Resources Canada, and managed by a joint CMHC-EMR Committee. The views expressed are the personal views of the author(s) and neither the Corporation nor EMR accepts responsibility for them.

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EXECUTIVE SUMMARY

Wind tunnel tests were conducted on a number of common configurations of furnace and fireplace flue terminations (i.e. exits) to determine the horizontal and vertical wind pressure coefficients for each configuration for a range of wind attack angles and to determine the restriction to flue flow created by each configuration.

The results indicate the following:

- *For any given set of wind conditions, there are wide variations in the performance of various chimney caps, in terms of their likely effect on the combustion venting performance of the chimney*
- *In deciding to use a cap on a particular chimney and in choosing a particular cap to use, the wind conditions likely to prevail at the top of the chimney and the performance characteristics of the candidate caps should be taken into account.*

To facilitate the informed selections of flue caps, it is suggested that Canadian standards related to flue caps be modified to incorporate detailed performance testing and rating of caps.

The test data was organized in a manner which would facilitate its use in calculations and modelling such as in the FLUE SIMULATOR computer program.

THE INFLUENCE OF FLUE TERMINATION CONFIGURATION

INTRODUCTION

As part of its ongoing study of combustion venting problems in Canadian houses, Canada Mortgage and Housing Corporation engaged the Scanada Sheltair Consortium to conduct studies of several aspects of chimney flue performance, including -

- the influence of thermal and flow design parameters on the performance of chimneys,

- the performance of flues shared by gas furnaces and water heaters,

- the influence of flue caps and dampers on chimney performance, and

- the performance of sealed, insulated venting systems for oil furnaces.

This report deals with one part of one of the above studies - the influence of flue caps on flue performance. The title has been changed to mention termination configuration rather than caps because performance data on capless flues is also of interest.

The other studies are reported on separately.

This part of the study consisted of the following tasks:

- a literature review

- a review of code requirements

- laboratory testing of a number of termination configurations

- analysis of the test results

- modification of FLUE SIMULATOR, a microcomputer-based model of thermal, pressure and flow interactions in the furnace/ flue/house system, to take into account the test results.

An attempt was also made to acquire for analysis any data from field tests of the influence of flue caps on venting performance; but no such data was found.

Characterization of Cap Performance

The main characteristic of a cap (or of any flue termination device) which determines its influence on the venting performance of the flue it terminates is the manner in which it adds wind pressure to or subtracts wind pressure from the pressure in the flue. This adds (or subtracts) directly to (from) the theoretical draft of the flue and is therefore key to the venting performance of the flue. A review of literature and codes, reported in the next section, indicated that the performance of caps is usually reported in terms of the change in static pressure across the cap, referenced to ambient pressure, for given wind and flue flow conditions. Results are either reported in terms of change in static pressure (e.g. in Pascals) or in terms of a non-dimensionalized expression called a wind pressure coefficient, which is the difference in static pressure across the cap divided by the dynamic pressure of the wind.

The dimensional presentation of results (e.g. Pascals) is useful to the heating systems industry which deals with draft as a common measure of venting ability. This dimensional reporting technique has been used by standards bodies to certify that caps do not alter the draft of a venting system by more than an allowable amount for a given set of wind conditions and flue flows.

Non-dimensional presentation of test data is a common procedure used by aerodynamicists to help generalize test results. The ability to generalize data makes non-dimensional reporting more suitable for modelling purposes, so this convention was followed in this study. Flue flow and wind speed are non-dimensionalized in terms of a velocity ratio (the flue gas velocity divided by the wind velocity).

PROBLEM DEFINITION

Although a chimney cap plays several roles (e.g. minimize rain penetration, prevent birds nests), its key role is to regulate the effects of wind on chimney draft. From the point of view of the operation of a combustion appliance, the ideal cap improves venting performance over that of a capless flue by minimizing the effect of variations in wind speed and wind direction on the draft of the system. High drafts caused by high winds draw excessive air from the house and may interfere with the combustion process in a naturally aspirating appliance or fireplace. Downdrafting winds, if unchecked, can cause spillage of flue gases into the house, and may also interfere with the combustion process.

Terrain, surrounding landscape, adjacent structures, roof shape and chimney shape can all produce a wide range of problematic winds at the flue cap. It is likely that no single cap design will satisfy all needs, nor should it since the above factors are rarely all present at a given installation. A chimney on a house in open, windy terrain (e.g. by the sea) might be subjected to high winds that are predominantly horizontal. A cap with a very low pressure coefficient for horizontal winds might be desirable to minimize the occurrence of high draft. On the other hand, a sheltered house that experiences depressurization on a regular basis might benefit from a cap with a high wind pressure coefficient. Such a cap might provide the extra margin needed to prevent prolonged backdrafting and spillage. A cap that can convert downdrafting winds into updraft would be an asset in those particular cases where downdrafting winds occur naturally due to terrain or adjacent tall structures. A cap that moderates the effect of updrafting winds might be desirable on a house with a steeply sloped roof.

THE INFLUENCE OF FLUE TERMINATION CONFIGURATION

The literature reviewed provided no analytic correlation between static pressure difference across the flue termination device and the factors which cause that difference: wind speed, wind angle of attack, and flue flow velocity. Therefore an attempt was made to derive such a correlation for modelling purposes. Accordingly, three key features of a cap were identified. These are:

- its ability to moderate updraft in horizontal winds
- its ability to dampen the effects of updrafting or downdrafting winds
- the amount of restriction to flow it creates

Three performance parameters are suggested from the above list:

- the cap's horizontal wind pressure coefficient,
- the cap's vertical wind pressure coefficient, and
- the effective flow area (EFA) of the cap or chimney exit.

The first two of these parameters could be combined into a total wind pressure coefficient which would apply for a given wind angle of attack. However, they have been kept separate in this study for reasons outlined below. The EFA of the cap (i.e. the effective orifice area of the cap) was chosen as a parameter to include the effect of the area of opening and the friction loss through that area.

The difficulty in deriving a functional relationship among the above parameters arises from the fact that for any given wind speed, wind angle, and flue flow velocity, there is only one measurable effect -the static pressure drop across the flue termination. Therefore, a hypothesis was formulated that the above three parameters are approximately constant for a given cap, and that the changes in static pressure at the base of the cap are solely due to changes in the three causal conditions: horizontal component of wind speed, vertical component of wind

speed, and flue flow velocity. This hypothesis was tested with the laboratory data generated for this study.

Therefore, the laboratory work and analysis undertaken in this study has focussed on deriving, via controlled tests, wind pressure coefficients and equivalent flow areas for typical flue termination configurations and using these to formulate general functional relationships between wind characteristics (speed and angle of attack) and the effect of wind on flues.

LITERATURE REVIEW

A key Dutch paper on the aerodynamic testing of flue caps (Ref.1) was located. Although translation into English was not available, the tabular and graphical test results reported for 14 termination configurations (including the capless vent that was used as a reference for all results) are self explanatory and are valuable additional data to this study. All test results are accompanied by clear photographs of the tested caps. The results are presented in terms of non-dimensional total wind pressure coefficients with, as far as can be determined given the language difficulty, no attempt to derive discharge coefficients.

One cap in particular (Cap #11 in the study, see Figure 1) showed the least variation in wind pressure coefficient as a function of wind angle and flow rate up the flue. This particular cap seems to eliminate all downward pressures - even for perfectly vertical downdrafting winds. This appears to be achieved at no expense to its performance at other wind angles.

The Dutch results are extremely informative on their own in that the performance of many caps can be compared directly on the basis of total wind pressure coefficients measured under different conditions. In designing or modelling, these coefficients can also be used on a "look-up" basis to calculate the performance of a specific termination configuration under specific conditions. However, wind pressure coefficient and flue flow velocity are mutually influential - a change in wind pressure causes a change in the flue draft, which causes a change in the flue flow velocity, which causes a different wind pressure coefficient to be operative. This process continues iteratively until equilibrium is reached. But the Dutch test results do not provide a means of dynamically linking wind pressure coefficient

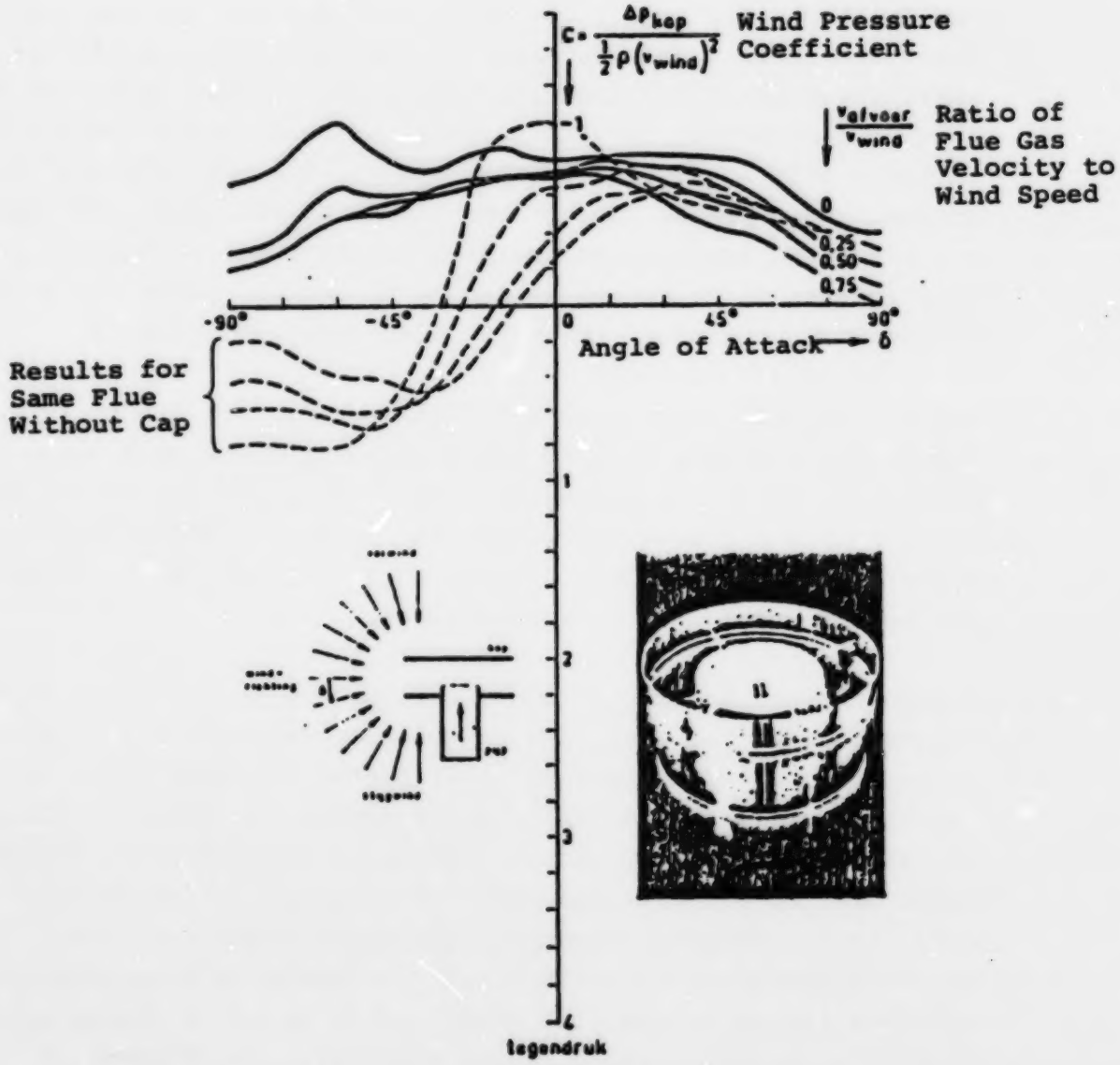

FIGURE 1: Cap #11 of the Dutch Test (Reference 1).

and flue flow velocity, which would allow a direct analytic solution to determine the equilibrium conditions. Repetitively looking up wind pressure coefficients in tables or graphs while carrying out iterative calculations is not a very satisfactory method. A means of closing this loop was sought in this project.

A second paper (tests performed at the Polytechnic Innovation and Resource Centre, Ireland - Ref. 2) contains laboratory test data on pressures developed in the chimney for four chimney cowls all with three annular fins arranged in different spacings and slopes. A second set of tests were performed on 4 other configurations - 8 caps in all were tested. Two test conditions were included: "open aspect" (no adjacent structure), and "cluttered" (our wording for a chimney adjacent to a sloped structure "representing a hip roof"). The test facility can be described as a full scale test installation including fireplace and chimney with a hot plate simulating the released heat of combustion and a smoke generator for flow visualization. Two configurations of the family of caps with three fins were shown to resist the effects of downdrafting winds, and indeed performed well under all test conditions. The two other cowls with three fins were undersized for the first chimney tested and caused restriction of the upward flow. When tested on a smaller flue, the restriction problem was eliminated and the latter two performed as the first two. These tests results confirm that the ratio of the equivalent flow area (EFA) of the cap to the actual area of the chimney is an important parameter to consider. Two caps without fins were shown to be inadequate in resisting severe downdrafting.

REVIEW OF CODE REQUIREMENTS

The only code reference to caps found is the Underwriters Laboratories Inc. (U.S.) UL 441 "Standard for Gas Vents". This standard includes a "Draft Loss and Wind Effects Test", which actually consists of three tests for -

1) flue termination resistance to flue flow under zero wind condition
2) flue termination resistance to flue flow under controlled flue flow and wind velocity.
3) wind-induced pressures for specified wind angles and velocities with no flue flow

The basic approach in the UL series of tests is to impose fixed flow conditions on the termination device (3 m/s flue flow velocity, 32.3 km/h wind speed) and measure the static pressure difference between the inside of the flue and ambient air. The criterion for assessment of the device is whether or not the resulting pressure difference is less than a maximum allowable value. This section of the UL standard is included as Appendix A.

It appears that the test facilities and procedures required for the UL tests are very similar to those that would have been used to develop the results presented in the Dutch paper, since the raw data measured in both tests are apparently identical. In fact, the results of a UL test could easily be non-dimensionalized and plotted as a single point on the graph shown in Figure 1.

The equivalent Canadian standard, ULC's CAN4-S605.-77, does not incorporate such tests although revision of the standard along these lines is being contemplated. This should be encouraged, as the UL tests are logical and relevant.

LABORATORY TESTING OF VARIOUS FLUE TERMINATION CONFIGURATIONS

Development of the Protocol

All test methods found in the literature involve the measurement of static pressure inside the flue relative to ambient pressure for different wind velocities and flue flows, including the case of zero flue flow (blocked flue). Testing approaches appeared to differ only in the means used to produce and control the flows, the range of conditions tested, and the way in which test results are reported.

The development of the test protocol for this study was an interactive effort between Scanada and the consultants hired for this study, Rowan, Williams, Davies and Irwin Inc. (RWDI) in Guelph, Ontario. Their original mandate was to test 5 termination devices so as to produce results similar to those reported in the Dutch paper, taking into account the limitations of the budget and the capabilities of the RWDI test facility. The resulting test protocol differed from the apparent Dutch protocol only in extent: the wind angle of attack range was +/- 45° instead of +/- 90°. Also, instead of controlling the velocity of the flue flow in four increments, as in the Dutch tests, the flue flow was set at two levels - zero velocity (blocked flue, as in the Dutch tests) and whatever velocity resulted from the flue being unblocked. This latter compromise in test procedure was made in view of the expense of setting up another fan, duct and control system that would be required to control the flue flow velocity and "wind speed" simultaneously.

When the above protocol was originally specified, it was thought that the second series of tests with the flues unblocked would also yield data that could be used in establishing the EFA's of

the caps. The upward flow velocities were measured by RWDI and non-dimensionalized by dividing by wind speed, as in the Dutch tests. The results are useful in themselves to qualify the performance of each cap, and can be used directly to suggest the order of magnitude of any reduction in cap wind pressure coefficient when there is a flue velocity. However, it was found that the EFA's of the caps cannot be directly deduced from the unblocked flue results as expected. The difficulty arises from the fact that the aerodynamics around the cap and the entrance losses in the test flue are unknowns which prevent direct calculation of the cap friction factor and hence EFA. RWDI therefore undertook further tests to measure the pressure drop across each termination configuration for various flue flows. These tests were conducted with no wind across the flue termination.

The testing thus consisted of 3 phases:

- measurement of "blocked flue" wind pressure coefficients, for each termination configuration, for a range of wind attack angles from 45° above horizontal to 45° below horizontal (as in the Dutch tests)

- measurement of "unblocked flue" wind pressure coefficients, for each termination configuration, for a range of wind attack angles from 45° above horizontal to 45° below horizontal (again as in the Dutch tests except that the air was allowed to flow freely in the flue. In the Dutch test, the flue flow rate was controlled by a second fan.)

- measurement of "no wind" pressure drops across each termination configuration at various levels of air flow through the flue

THE INFLUENCE OF FLUE TERMINATION CONFIGURATION

Four different commercially available caps commonly used on Canadian houses were tested, as well as a mock-up of a standard capless masonry chimney. These were:

- a large A-vent cap apparently designed to reduce wind effects

- a standard B-vent cap commonly used in Ottawa and probably extensively across North America (a sketch of this cap is in the ASHRAE HANDBOOK of EQUIPMENT)

- the aerodynamically conceived Aerocowl cap

- a standard rain cap and grill for a fireplace masonry chimney

Details of these termination configurations are shown in Appendix B.

RWDI's report is included in Appendix C along with photographs of the caps investigated in this study.

ANALYSIS OF TEST RESULTS

To review, it was indicated in the PROBLEM DEFINITION section that there is a need to develop a functional relationship among the three causal conditions - horizontal component of wind speed, vertical component of wind speed and flue flow velocity - and the resulting static pressure drop (rise) inside the flue. Three parameters were identified for this task:

- the horizontal wind pressure coefficient
- the vertical wind pressure coefficient
- the equivalent flow area of the termination device.

The hypothesis is that these three distinct parameters fully determine the performance of a given termination configuration for all combinations of wind speed, wind angle,and flue flow velocity. If such a hypothesis were correct, the task of modeling the performance of termination devices would be facilitated. This hypothesis is used to analyze the laboratory test results generated for this project by RWDI.

Horizontal Wind Pressure Coefficient - No Flue Flow

The first set of results address the first two parameters of the caps: the horizontal and vertical wind pressure coefficients for the no flue flow condition. The bar chart in Figure 2 shows the horizontal wind pressure coefficient for each cap. The extremely high wind pressure coefficient of the open masonry chimney is apparent. RWDI explains that this is likely due to the interaction of the wind and the large concrete chimney cap (as opposed to flue cap). The height of the protruding clay tile liner above this cap likely plays an important role in producing the effective wind pressure coefficient for such open masonry flues.

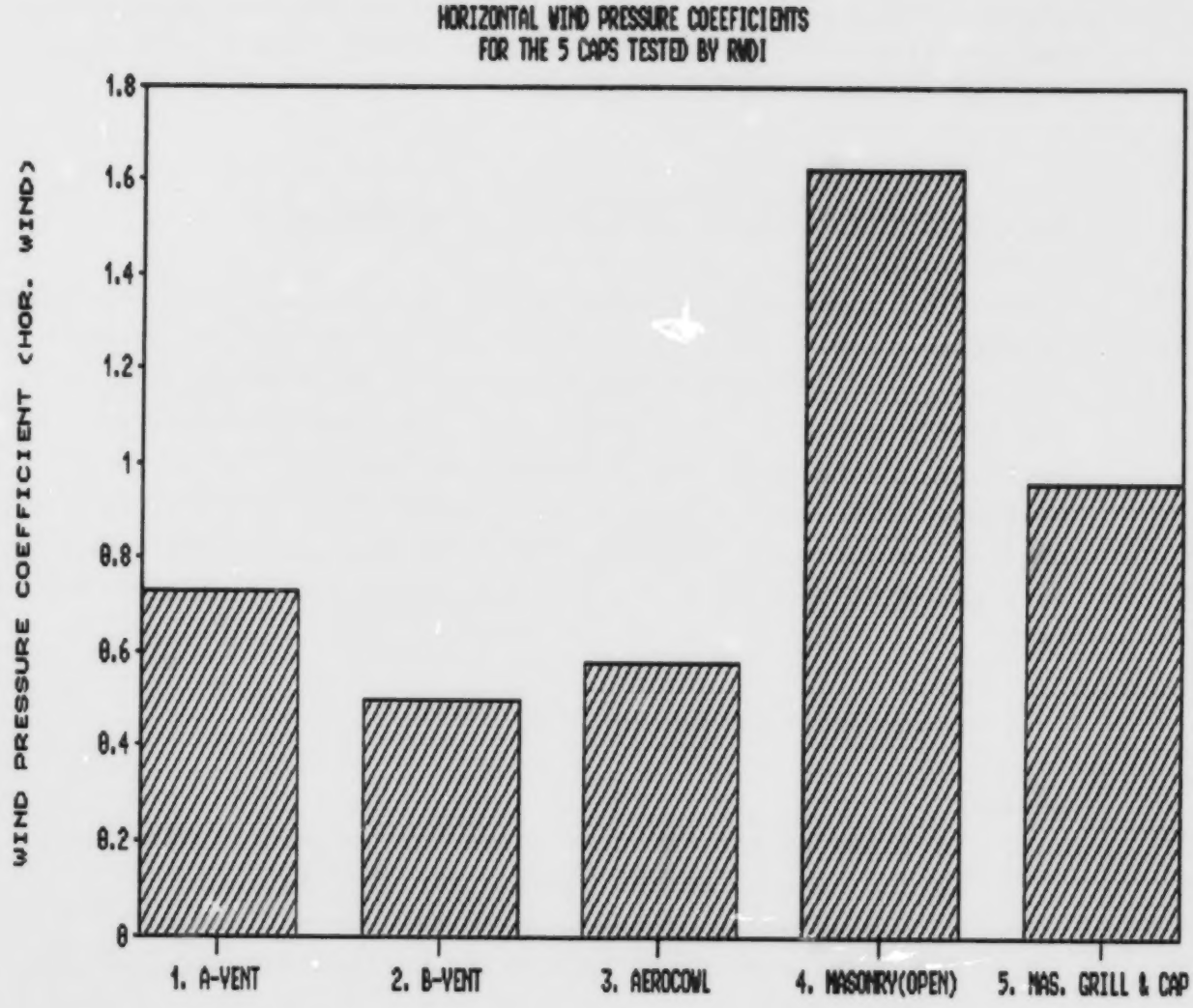

FIGURE 2: Horizontal wind pressure coefficients for the 5 caps tested by RWDI.

The four flue caps perform similarly to one another in horizontal winds. The flue cap on the masonry chimney has the effect of reducing the horizontal wind pressure coefficient by 40% from that of the open masonry chimney.

Vertical Wind Pressure Coefficient - No Flue Flow

Since wind pressure coefficients were not measured with an angle of attack of 90° (i.e. vertical wind), the derivation of the vertical wind pressure coefficient had to be based on the previously discussed assumption that horizontal and vertical wind pressure coefficients are constant and that the change in the measured total wind pressure coefficient (Ct) was entirely due to changes in the relative contribution of the horizontal and vertical wind vectors. The equation representing this assumption is:

$$C_h \cdot \tfrac{1}{2} \cdot \rho \cdot V_h^2 + C_v \cdot \tfrac{1}{2} \cdot \rho \cdot V_v^2 = C_t \cdot \tfrac{1}{2} \cdot \rho \cdot V_t^2$$

where:

C_h is fixed at the measured value for horizontal winds
ρ is the density of the outside air (kg/m^2)
V is the velocity of the wind (m/s)
h,v and t are subscripts indicating horizontal, vertical and total components

From the geometric relationship between the wind vectors, the above expression can be manipulated to derive the following expression from which Cv is derived:

$$C_v = (C_t - C_h \cdot \cos\theta^2)/\sin\theta^2$$

where:

θ is the angle of attack of the wind measured from the horizontal

All test results for non-horizontal flows can thus be expressed in terms of the effective vertical wind pressure coefficient. This highlights how each cap configuration deals with the vertical component. Figures 3 to 6 show the effect that each cap has, based on the above equation. Figures 3 and 4 show the results for downdrafting winds of 30° and 45° respectively. All four caps have the effect of converting the downdrafting component to updraft pressures in the chimney, as indicated by the positive vertical wind pressure coefficients. On the other hand, the open chimney does not resist the downdraft. It can also be seen that the hypothesis that the vertical wind pressure coefficient is constant regardless of wind angle is not entirely correct. Although the A-vent, B-vent and open masonry chimney have similar vertical coefficients for -30° and -45°, the Aerocowl and masonry cap/grill arrangement show great differences in these coefficients for the two downdrafting angles shown. The hypothesis of constancy of component wind pressure coefficients appears not to be valid. Nevertheless, these results are instructive on their own.

The results for the updrafting winds of 30° and 45° shown in Figures 5 and 6 are more surprising. At 30° updraft the A-vent cap neutralizes the updrafting component of the wind vector, the B-vent and masonry caps (Caps 2 and 5) convert the updrafting component to small updraft pressures, but the Aerocowl and open masonry chimneys convert these vertical components to substantial downward vectors resulting in sharp drops of the total wind pressure coefficient at that angle. The total wind pressure coefficients nevertheless remain positive (i.e. slight updraft)

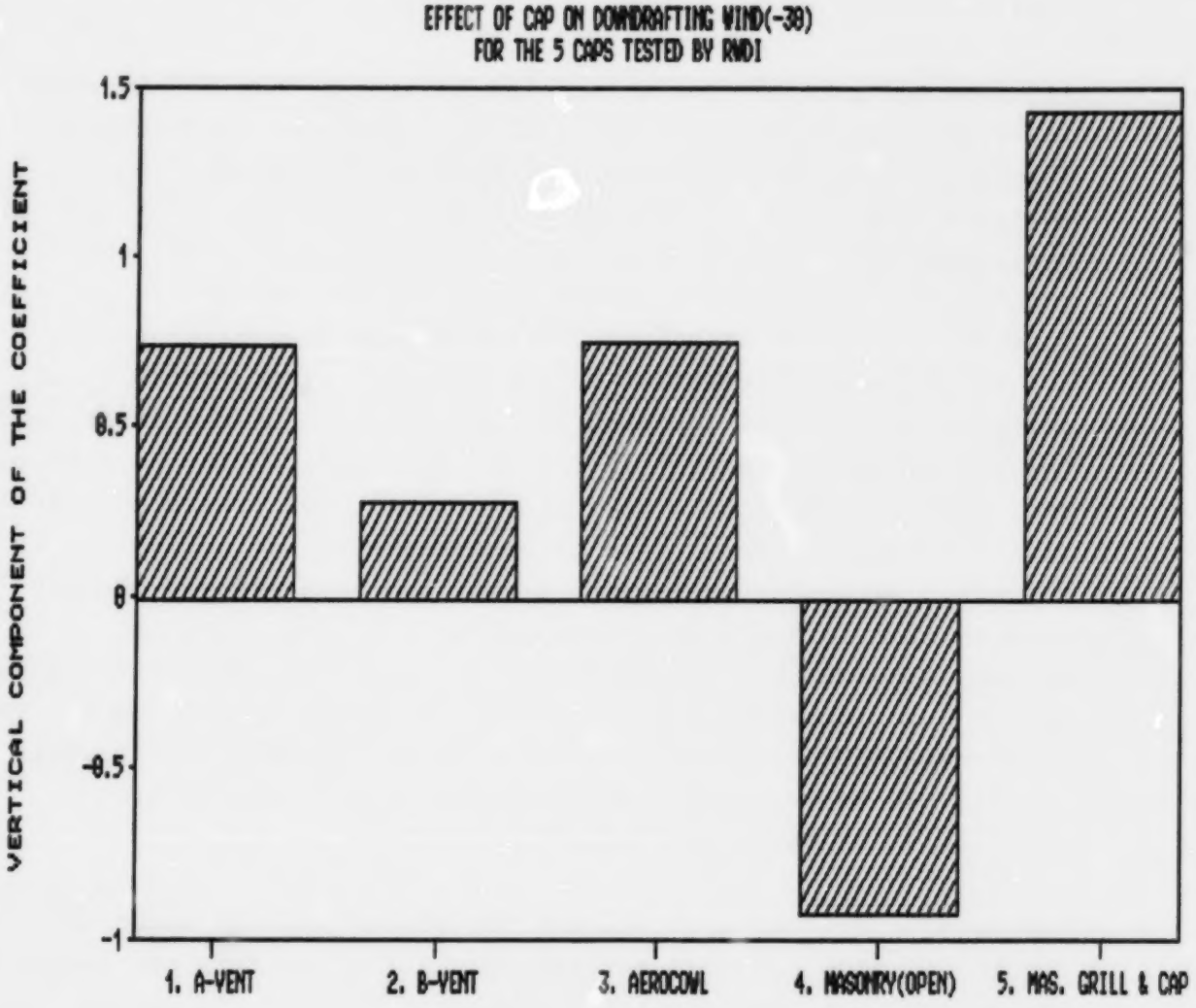

FIGURE 3: Effect of cap on downdrafting wind (-30°) for the 5 caps tested by RWDI.

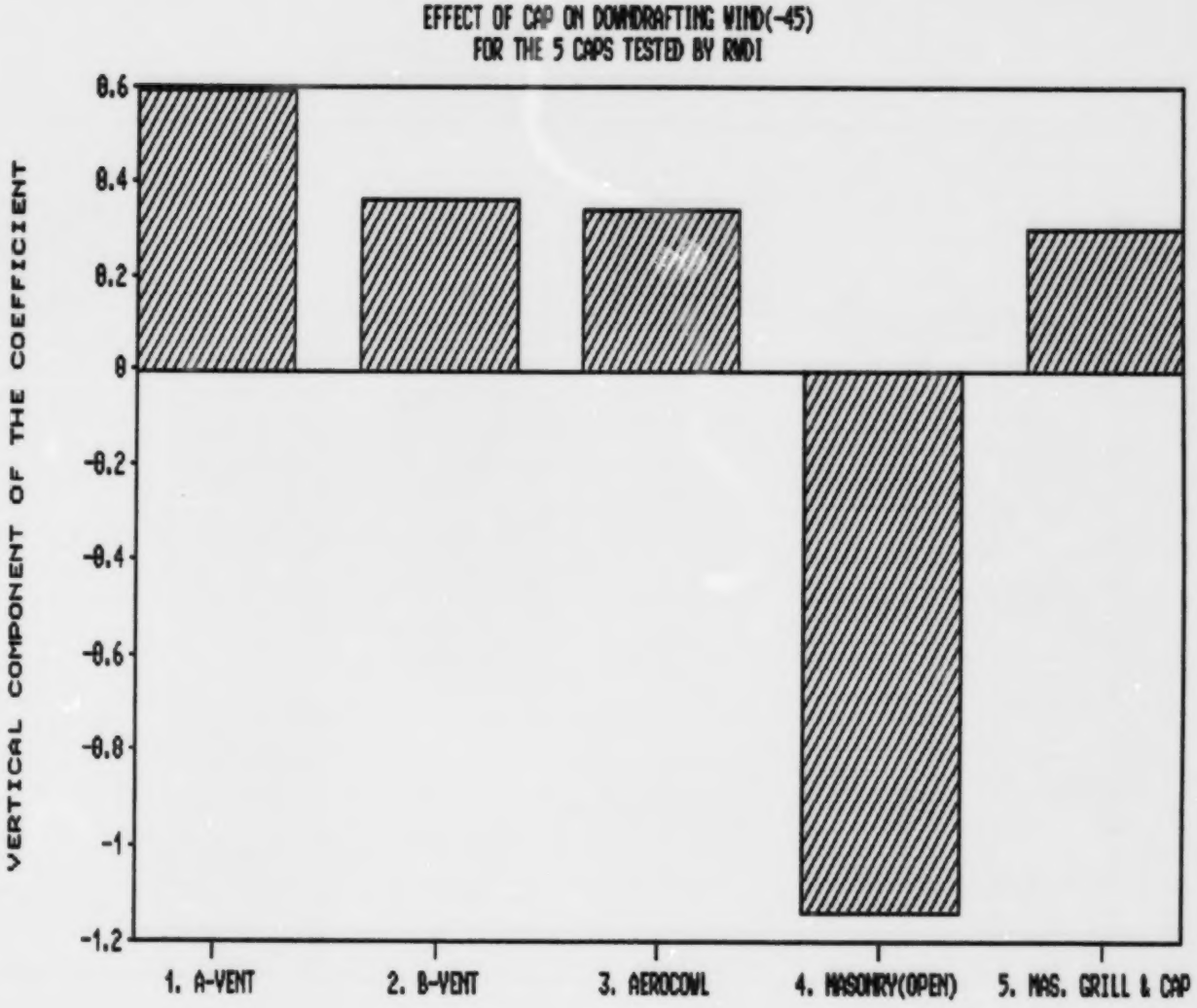

FIGURE 4: Effect of cap on downdrafting wind (-45°) for the 5 caps tested by RWDI.

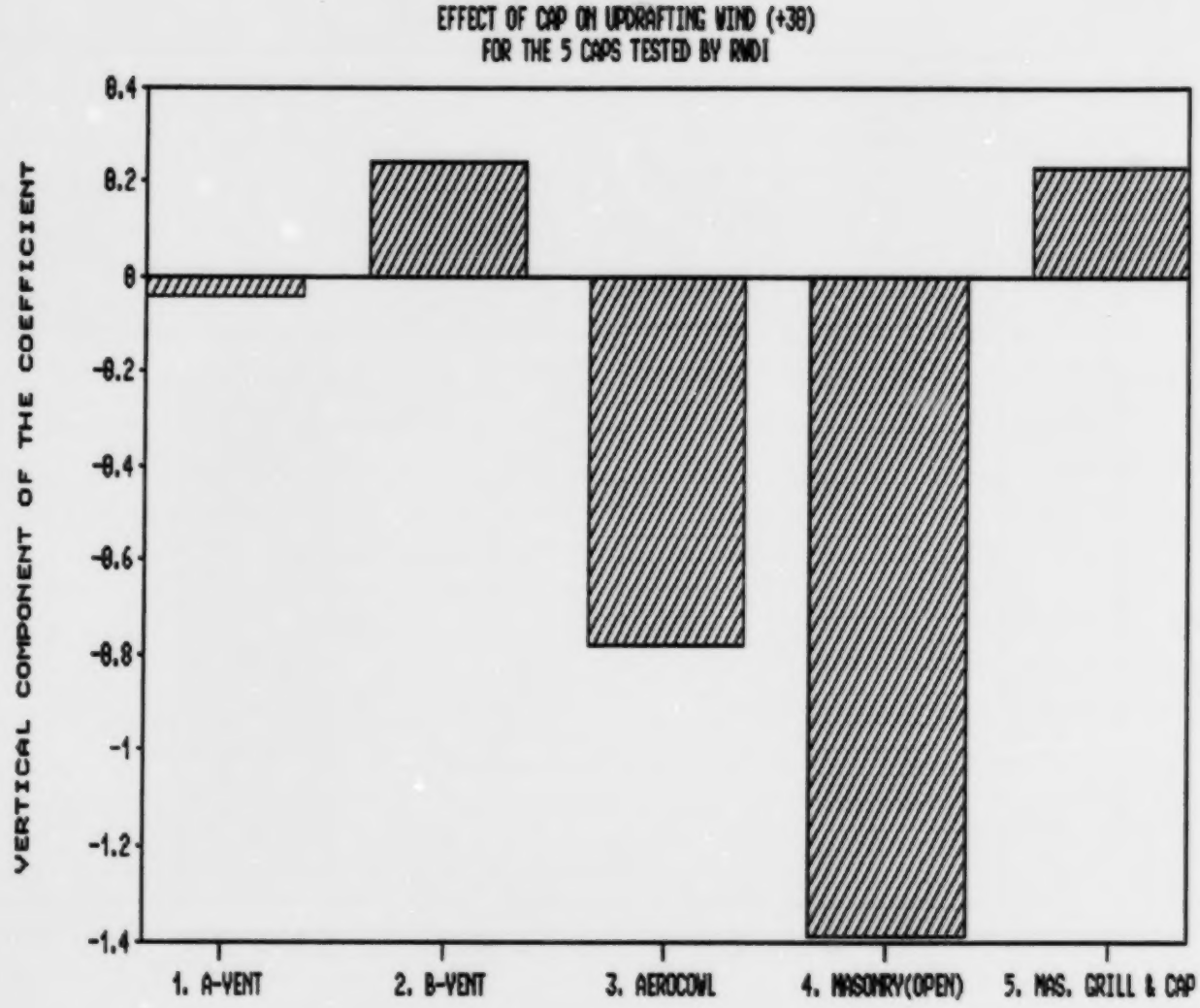

FIGURE 5: Effect of cap on updrafting wind (+30°) for the 5 caps tested by RWDI.

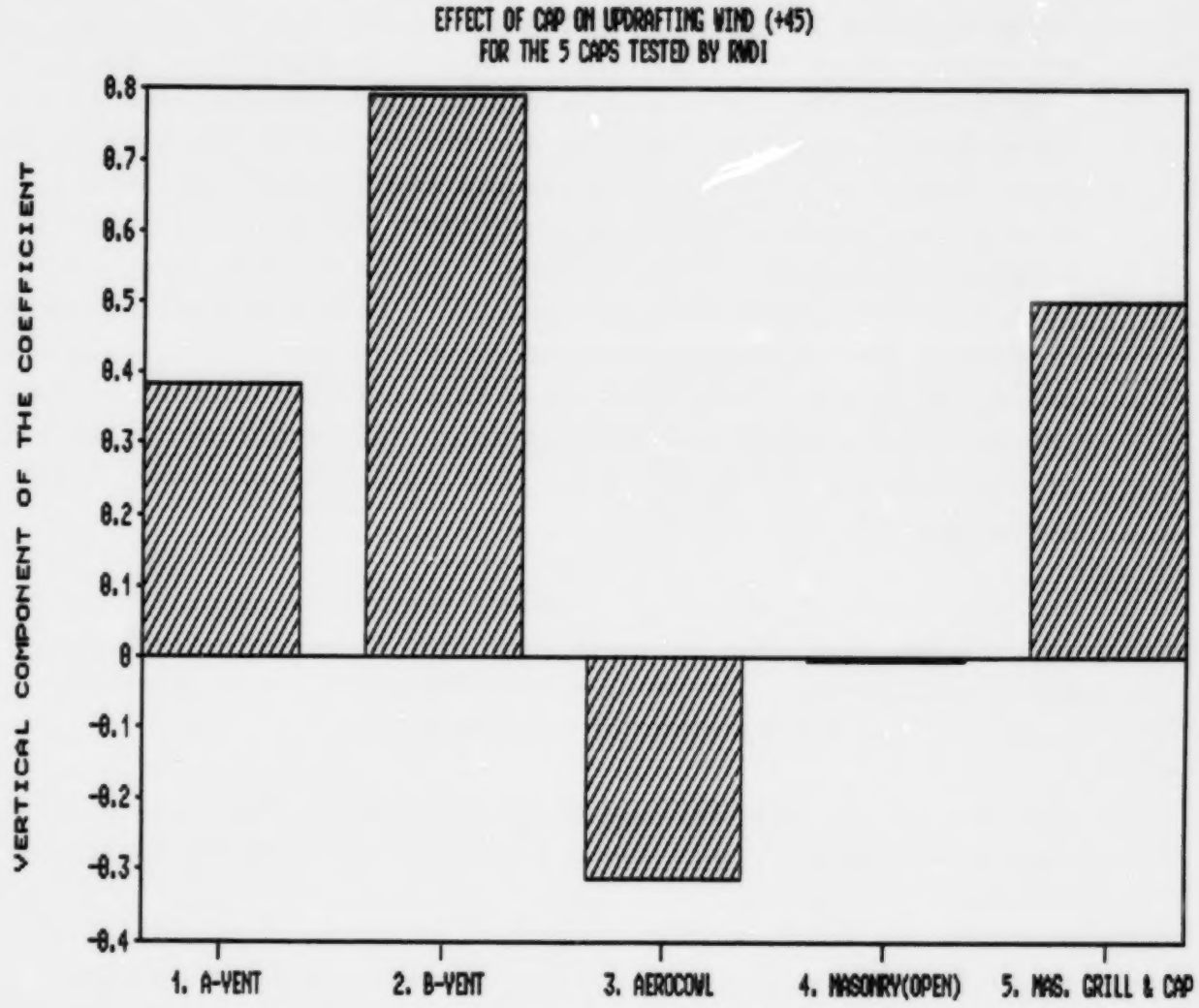

FIGURE 6: Effect of cap on updrafting wind (+45°) for the 5 caps tested by RWDI.

because of their respective horizontal components which are updrafting in both cases. At 45° updraft, all configurations show some improvement in the vertical component over the 30° case, as would be expected, but the Aerocowl has not totally recovered and still produces a downdrafting component. RWDI suggests that the key to understanding these results lies in the chimney structure below the cap and the design of the base of the caps. The A-vent, B-vent and masonry cap all have protruding lips at their base. These may foil the updrafting air that is flowing up the face of the chimney. The Aerocowl does not have such a lip, and because of the thickness of the insulating jacket on the A-vent, the fins of the Aerocowl are just about flush with the outer jacket of the vent. For this or other unknown reasons, the Aerocowl yielded the smallest total wind pressure coefficient of all configurations, and that occurred at the steepest updrafting wind condition tested.

The hypothesis of constant component wind pressure coefficients is strained even more with positive wind angles of attack (i.e. updrafting winds) - in fact, there appears to be no pattern emerging from a comparison of Figures 5 & 6.

Further correlations between component wind pressure coefficients were attempted with more success. These are reported in Appendix D.

Table 1 summarizes the wind pressure coefficient results and shows the effect that each flue termination will have on net driving pressure for each of two wind speeds. Note that, with a 20 km/h wind, most termination configurations will increase the house depressurization limit well beyond the levels of depressurization likely to be encountered in houses.

TABLE 1A MEASURED WIND PRESSURE COEFFICIENTS FOR A BLOCKED FLUE

WIND ANGLE	1 A-VENT	2 B-VENT	3 Aerocowl	4 OPEN	5 MASON. CAP&GRILL
-45	0.662	0.432	0.461	0.242	0.629
-30	0.731	0.446	0.621	0.989	1.078
0	0.728	0.503	0.580	1.626	0.958
30	0.536	0.439	0.241	0.873	0.777
45	0.556	0.646	0.136	0.812	0.731

TABLE 1B INCREASE IN HOUSE DEPRESSURIZATION LIMIT DUE TO WIND (Pa)

WIND SPEED - 10 km/hr

WIND ANGLE	1 A-VENT	2 B-VENT	3 Aerocowl	4 OPEN	5 MASON. CAP&GRILL
-45	3.3	2.2	2.3	1.2	3.1
-30	3.6	2.2	3.1	4.9	5.4
0	3.6	2.5	2.9	8.1	4.8
30	2.7	2.2	1.2	4.3	3.9
45	2.8	3.2	0.7	4.0	3.6

TABLE 1C INCREASE IN HOUSE DEPRESSURIZATION LIMIT DUE TO WIND (Pa)

WIND SPEED - 20 km/hr

WIND ANGLE	1 A-VENT	2 B-VENT	3 Aerocowl	4 OPEN	5 MASON. CAP&GRILL
-45	13.2	8.6	9.2	4.8	12.5
-30	14.6	8.9	12.4	19.7	21.5
0	14.5	10.0	11.5	32.4	19.1
30	10.7	8.7	4.8	17.4	15.5
45	11.1	12.9	2.7	16.2	14.6

Effective Flow Area Through the Cap

The results of the pressure/flow, no wind tests have been fitted to empirical curves and translated into EFA and friction factor terms as shown in Table 2. The EFA has been non-dimensionalized in the table by dividing it by the actual cross-sectional area of the flue. The non-dimensionalized EFA allows for comparison of the performance of the termination configurations even though only two of the flues in the tests had the same cross sectional area (the masonry flues). In that flow through a sharp edged orifice experiences contraction losses as well as the loss of the dynamic head term (discharge loss), a desirable characteristic of a termination configuration would be a non-dimensionalized EFA greater than 1. An "EFA/A" of 1 or less suggests that the cap would cause a significant contraction in the flow streamlines.

The key results in this table are the friction factor ("K") of each cap (the friction factor is the number of dynamic heads dissipated by the cap) and the ratio of the cap EFA to the area of the flue opening, explained above. As a reference point, one would expect the friction factor of an uncapped chimney to be about 1.0. That is, all of the dynamic pressure available at the top of the chimney is dissipated above the chimney. In fact, the open chimney did better than this with a "K" factor of 0.71, implying that some recovery of the available dynamic head was occurring at the top - this is achievable by diffusion of the flow stream at the exit. The "EFA/A" ratio was the highest for this chimney, as expected (i.e. the greater the relative size of the equivalent orifice the better). The caps rank in order of highest to lowest "EFA/A" ratio as follows:

1 Cap & Grill; 2 A-vent; 3 B-vent; 4 Aerocowl

TABLE 2 EFA TEST RESULTS FOR THE 5 CHIMNEY CAPS TESTED BY RWDI

	TEST RESULTS						RESULTS OF THE CURVE FITTING OF TEST DATA				
							C	n	EFA	K	EFA/A
A-VENT	FLUE OPENING AREA= 0.0248 m2						0.0302	0.508	0.0392	1.05	1.6
DEPRESS Pa	FLOW CFM	FLOW L/s	VEL m/s	DYNAMIC (Pa)	TOTAL dP (Pa)	FLOW L/s	FITTED FLOW L/s		FITTED dP		
1	286	135	5.45	17.9	18.9	135	135		18.8		
3	509	240	9.69	56.8	59.8	240	241		59.7		
2	544	257	10.36	64.9	66.9	257	256		68.2		
3	576	272	10.97	72.8	75.8	272	272		76.4		
							C	n	EFA	K	EFA/A
B-VENT	FLUE OPENING AREA= 0.0127 m2						0.0139	0.5	0.0177	1.38	1.4
DEPRESS Pa	FLOW CFM	FLOW L/s	VEL m/s	DYNAMIC (Pa)	TOTAL dP (Pa)	FLOW L/s	FITTED FLOW L/s		FITTED dP		
19	276	130	10.26	63.7	82.7	130	126		87.9		
52	401	189	14.91	134.5	186.5	189	190		185.6		
60	437	206	16.25	159.8	219.8	206	206		220.5		
62	445	210	16.55	165.7	227.7	210	210		228.6		
							C	n	EFA	K	EFA/A
Aerocowl	FLUE OPENING AREA= 0.0231 m2						0.0157	0.5	0.0200	3.58	0.9
DEPRESS Pa	FLOW CFM	FLOW L/s	VEL m/s	DYNAMIC (Pa)	TOTAL dP (Pa)	FLOW L/s	FITTED FLOW L/s		FITTED dP		
51	282	133	5.77	20.1	71.1	133	132		72.0		
90	364	172	7.44	33.5	123.5	172	174		119.9		
130	420	198	8.59	44.6	174.6	198	207		159.6		
137	468	221	9.57	55.4	192.4	221	218		198.2		

TABLE 2 EFA TEST RESULTS FOR THE 5 CHIMNEY CAPS TESTED BY RWDI (continued)

	TEST RESULTS						RESULTS OF THE CURVE FITTING OF TEST DATA				
							C	n	EFA	K	EFA/A
OPEN CHIMNEY	FLUE OPENING AREA= 0.0439 m2						0.0670	0.5	0.0853	0.71	1.9
DEPRESS Pa	FLOW CFM	FLOW L/s	VEL m/s	DYNAMIC (Pa)	TOTAL dP (Pa)	FLOW L/s	FITTED FLOW L/s		FITTED dP		
-3	532	251	5.72	19.8	16.8	251	275		14.1		
-6	540	255	5.81	20.4	14.4	255	254		14.5		
-8	610	288	6.56	26.1	18.1	288	285		18.5		
							C	n	EFA	K	EFA/A
CAP & GRILL	FLUE OPENING AREA= 0.0439 m2						0.0565	0.5	0.0719	1.00	1.6
DEPRESS Pa	FLOW CFM	FLOW L/s	VEL m/s	DYNAMIC (Pa)	TOTAL dP (Pa)	FLOW L/s	FITTED FLOW L/s		FITTED dP		
-1	592	280	6.37	24.5	23.5	280	274		24.5		
0	594	281	6.39	24.7	24.7	281	281		24.7		
2	605	286	6.51	25.6	27.6	286	297		25.6		

Correlation Between Blocked and Unblocked Pressure Coefficients

Ideally, it would be desirable to be able to predict the drop in effective wind pressure coefficient as a function of flue flow. This would permit the cap performance to be simulated rigorously not only at the stalled flue condition (for which the "blocked wind pressure coefficient" applies), but for all flue flow situations. Figure 7 shows a plot of the pressure drop at the chimney top with the flue unblocked versus the pressure drop with the flue blocked. This plot is for a 10 km/h wind and includes all termination configurations and all wind attack angles. If flue flow had no effect on wind pressure coefficient, these points would all fall on the 45° line of perfect agreement. The

amount that any point is above or below that line is a measure of how much flue flow increases or reduces the wind pressure coefficient for that flue termination. Systematic plots of this difference against flue flow velocity, dynamic pressure in the flue, and friction loss of the cap (plots not shown) yielded no systematic relationship from this limited amount of data that could be used to predict this effect. This is not to say that the points shown in Figure 7 are completely random - they are not. The vertical distance from each point to the 45° line in the plot is the measure of the change in static pressure inside the flue due to unblocking the cap. These changes seem to be systematic for the A-vent and B-vent. In fact, a line drawn below the the 45° line and diverging slightly at higher pressure would fit the points nicely. However, it has not been possible to relate this trend to causal conditions (i.e. wind angle of attack and flue flow velocity) within the scope of this project. The first attempts at drawing these correlations are shown in Appendix D.

This failure to correlate the drop in wind pressure coefficient with flue flow was predicted by RWDI. They indicated that the drop in wind pressure coefficient is due to a combination of flow friction in the cap and the foiling of the aerodynamic flow patterns around the cap by the flue flow.

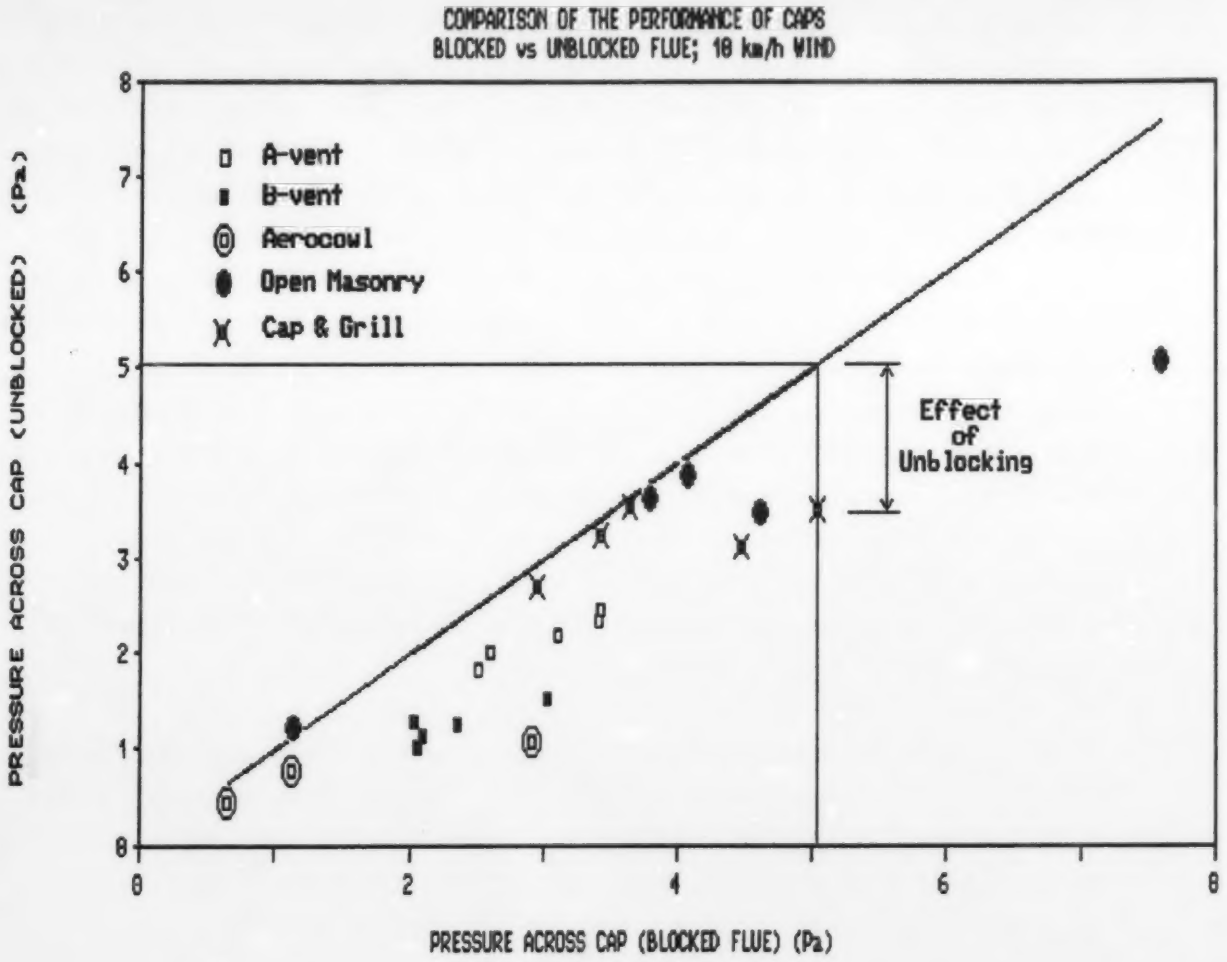

FIGURE 7: Comparison of the performance of caps blocked vs unblocked flue; 10 km/h wind.

MODIFICATION OF THE FLUE SIMULATOR MODEL

The results of this study have been incorporated in FLUE SIMULATOR, a microcomputer-based model of thermal, pressure and flow interactions in the furnace/flue/house system developed for CMHC by Scanada Consultants Limited. No modification of the model's basic algorithms was required. However, the wind pressure coefficients and EFA values were previously fixed values in the program code. The program has now been modified to accept these as user inputs. Tables of values for these properties for the five terminations tested have been included in the FLUE SIMULATOR User's Manual.

Because no systematic correlation could be found between wind pressure coefficients with the flue blocked and unblocked, FLUE SIMULATOR is not able to model the dynamic relationship between wind pressure coefficient and flue flow. As an approximation, the user of the model must pick the coefficient that best suits the situation being investigated. If a low-draft/low-flue-flow start-up is being investigated then the choice of the "blocked flue" wind pressure coefficient for the wind angle of attack being studied is recommended. For modelling of full heat-up/cool down cycles, then the appropriate "unblocked flue" coefficient should be used.

These modifications are described in more detail in the report "1st Quarter, 1987 Modifications to Flue Simulator".

CONCLUSIONS

The results of the laboratory testing of flue caps undertaken in this project has generated useful data that can be used directly in the modelling of the combustion venting process. This data has also highlighted the differences in performance of the caps tested -and the variations were considerable. Based on the performance of the caps tested, it should be possible to rectify problematic downdrafting on the one hand, or improve the driving pressure due to wind action on the other - given the particular problem to be addressed. It was shown that with a 20 km/h wind speed, and for almost all wind angles tested, the 4 caps could develop more than enough driving pressure to counteract even the most severe house depressurizations.

As mentioned under "REVIEW OF CODE REQUIREMENTS", Underwriters' Laboratories of Canada should be encouraged to incorporate pressure and flow tests for caps, along the lines of those incorporated in the UL standard, in their standard for gas vents. Indeed, they could consider going further and include tests similar to those used by RWDI in this project; i.e. testing for a broad range of wind angles and speeds rather than a single set of conditions. These tests could form the basis for rating the performance of flue caps. Such a rating system would allow informed decisions about the choice of the right cap for a given situation to be made by installers of vents and caps and thus would help avoid the installation of flue cap that are counter-productive to the venting process.

REFERENCES

1. DRIE ONDERZOEKEN NAAR DE WERKING VAN KANALEN VOOR NATUURLIJKE VENTILATIE, WAARBIJ NAGEGAAN IS DE INVLOED VAN PLAATS EN HOOGTE VAN DE UITMONDING, VAN DE BEBOUWING IN DE OMGEVING ENVAN DE VPRM VAN DE UITMONDING, Ing. W. f. de Gids en Ing. Ph. L. den Ouden.

2. Chimney Cowl Laboratory Tests, Mitchell, A.W, Polytechnic Innovation and Resource Centre

3. ASHRAE Equipment Fundamentals, 1986, Chapter 27.

APPENDIX A

EXTRACT FROM STANDARD UL 441
"STANDARD FOR GAS VENTS"

21. Draft Loss and Wind Effects Test

21.1 A cap for direct attachment to a gas-vent pipe and a cap of a roof assembly or roof jack shall not excessively impede the flow of flue gases in still air as determined by methods of test described in paragraphs 21.2 and 21.3.

21.2 The cap under test is to be mounted on a continuous length of test gas vent or on its roof assembly or roof jack as mounted on a continuous length of test vent. The test gas vent is to be capable of being sealed so that there will be no flow. Static pressure within the test vent is to be determined by a pitot tube, pressure tap, or piezometer ring located 12 inches (300 mm) below the point of cap attachment. Pressure readings are to be taken with an instrument capable of being read to the nearest 0.001 inch (0.025 mm) of water column (w.c.). The test gas vent is to be the same nominal diameter as the cap under test. The cap manufacturer may furnish a section of test gas vent not over 12 inches (300 mm) long, having a typical joint connecting to the cap. This pipe section may be left in place on the end of the test vent for the test for wind effects where applicable. All joints in the test gas vent between the inlet end and the cap under test are to be sealed or taped against leakage for all tests.

21.3 An upward air velocity of 10 feet (3.05 m) per second [velocity pressure 0.023 inch (0.60 mm) w.c.] is to be established in the test gas vent with no cap on it and the static pressure measured. The cap under test is to be placed on the test vent, roof assembly, or roof jack and an upward velocity of 10 feet (3.05 m) per second is to be established in the test vent, and the static pressure measured. The difference between the static pressures is not to exceed 0.034 inch (0.86 mm) w.c.

21.4 A cap for direct attachment to a gas-vent pipe having an internal diameter of 12 inches (300 mm) or less shall not excessively impede the flow of flue gases due to wind action at angles from 45 degrees below horizontal to 45 degrees above horizontal as determined by methods of test described in paragraph 21.5 and 21.6.

21.5 The gas-vent cap under test is to be mounted on a continuous length of test gas vent as described in paragraph 21.2 which can be fixed in position at the wind generator outlet to obtain various elevation angles of wind approach. The wind generator is to be capable of producing a uniform wind front at 20 miles per hour (32 km/h) velocity [29.3 feet per second (8.93 m/s); velocity pressure 0.192 inch (4.88 mm) w.c.] over an area described by a diameter not less than 12 inches (300 mm) greater than the maximum width of the cap under test. The velocity is to be considered uniform if the variation at any point does not exceed 5 percent of the average velocity. The configuration of test gas vent and cap is to be such that the cap remains centered in the wind front during rotation about any axis.

21.6 With the cap in place on the test vent and an upward air velocity of 10 feet per second (3.05 m/s) in the test vent, a simulated wind front of 20 miles per hour (32 km/h) is to be directed at the cap at elevation angles of 45 degrees below horizontal to 45 degrees above horizontal at 15 degree intervals. The static pressure in the test gas vent, determined by averaging pressure at horizontal with the three pressures below horizontal, is not to increase by more than 0.068 inch (1.73 mm) w.c. beyond the reading obtained in accordance with paragraph 21.3, with no cap on the gas vent. The static pressure in the test vent, determined by averaging pressure at horizontal with the three pressures above horizontal, similarly, is not to increase by more than 0.068 inch (1.73 mm) w.c. beyond the reading obtained in accordance with paragraph 21.3, with no cap on the gas vent. Caps which are nonsymmetrical and are intended for mounting in any orientation about their vertical axis are to be rotated and tested in any position in azimuth that imposes the highest draft loss.

21.7 A cap for direct attachment to a gas-vent pipe having an internal diameter of 12 inches (300 mm) or less shall induce an adequate updraft effect when subjected to wind flow past the cap, as determined in accordance with the method of test described in paragraphs 21.8 and 21.9.

21.8 The arrangement described in paragraphs 21.2 and 21.5 is to be employed. The cap is to be placed on the test gas vent and centered in the wind front. The inlet to the test vent is to be sealed so that there is no flow. A 20 mile per hour (32 km/h) wind front is to be directed at the cap at elevation angles of 45 degrees below horizontal to 45 degrees above horizontal at 15 degrees intervals. Caps which are nonsymmetrical and are intended for mounting in any orientation about the vertical axis are to be rotated and tested at whatever position in azimuth creates the minimum updraft capability.

21.9 At angles of wind approach in elevation and azimuth described in paragraph 21.8, the cap under test is to develop an updraft as evidenced by an average negative (below atmospheric) static pressure within the sealed test gas vent equal to or more negative than 0.034 inch (0.86 mm) w.c. For winds from below horizontal, the static pressure is to be determined by averaging pressure at horizontal with the three pressures below horizontal. For winds from above horizontal, the static pressure is to be determined by averaging pressure at horizontal with the three pressures above horizontal. No individual pressure reading at any angle above or below horizontal is to indicate a positive (above atmospheric) pressure.

widest average dimension of the roof housing, whichever is greater, multiplied by the greatest height measured from the roof to the top of the gas vent.

22.4 A force equivalent to the product of the projected area multiplied by the assumed wind pressure of 30 pounds per square foot (1435 Pa) is to be applied in a horizontal direction to the surface assumed to be exposed to wind. If a uniform surface force cannot be applied, the force is to be applied at the middle of the height used to calculate the force in a manner such as to evenly distribute the force over as much of the surface as practical. See Figure 22.1. The force is to be sustained for a period of 1 hour as a static force.

APPENDIX B

DETAILS OF TERMINATION CONFIGURATIONS TESTED

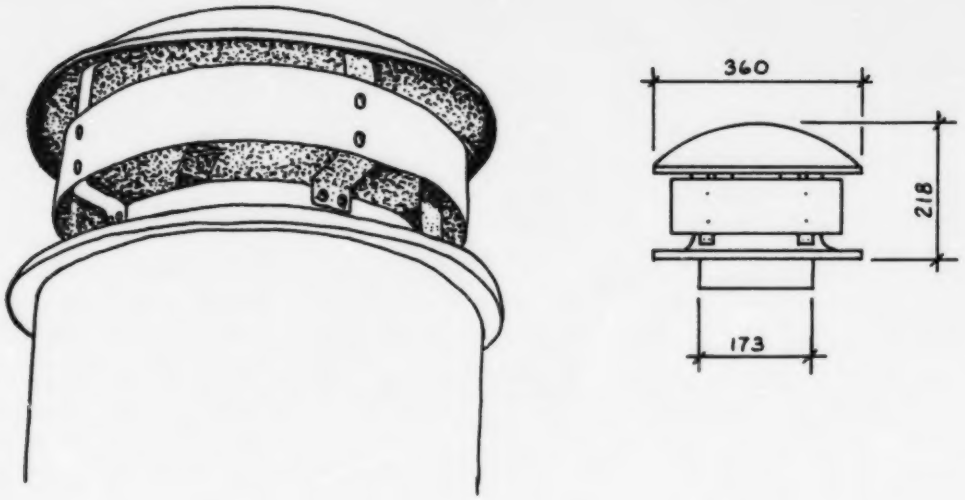

FIGURE B1: A-vent

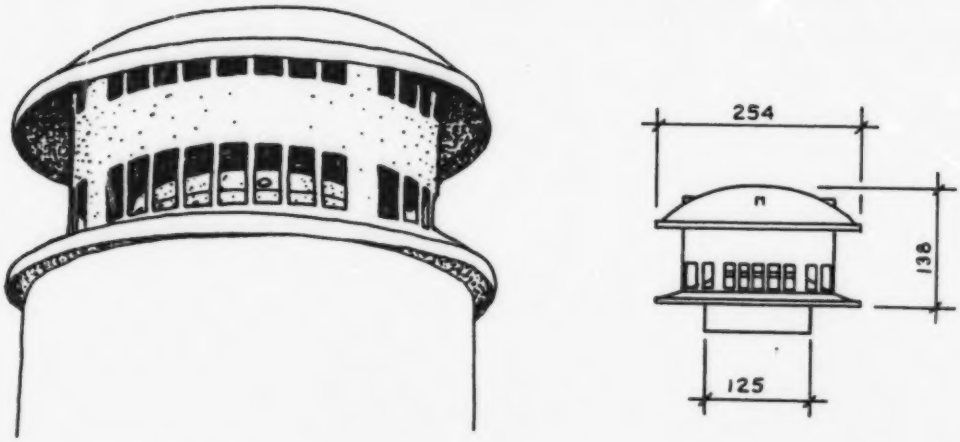

FIGURE B2: B-vent

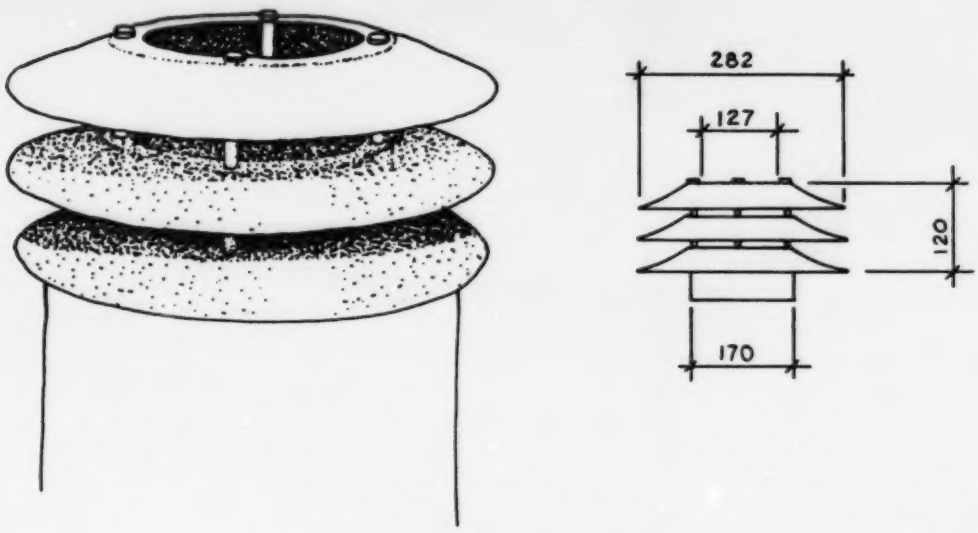

FIGURE B3: Aerocowl

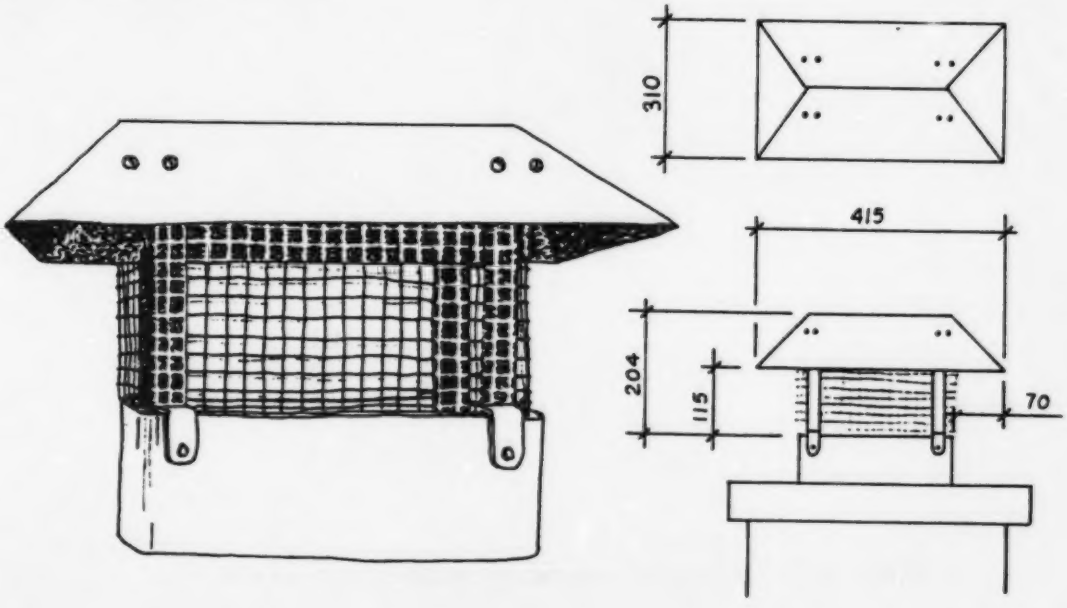

FIGURE B4: Cap & Grill

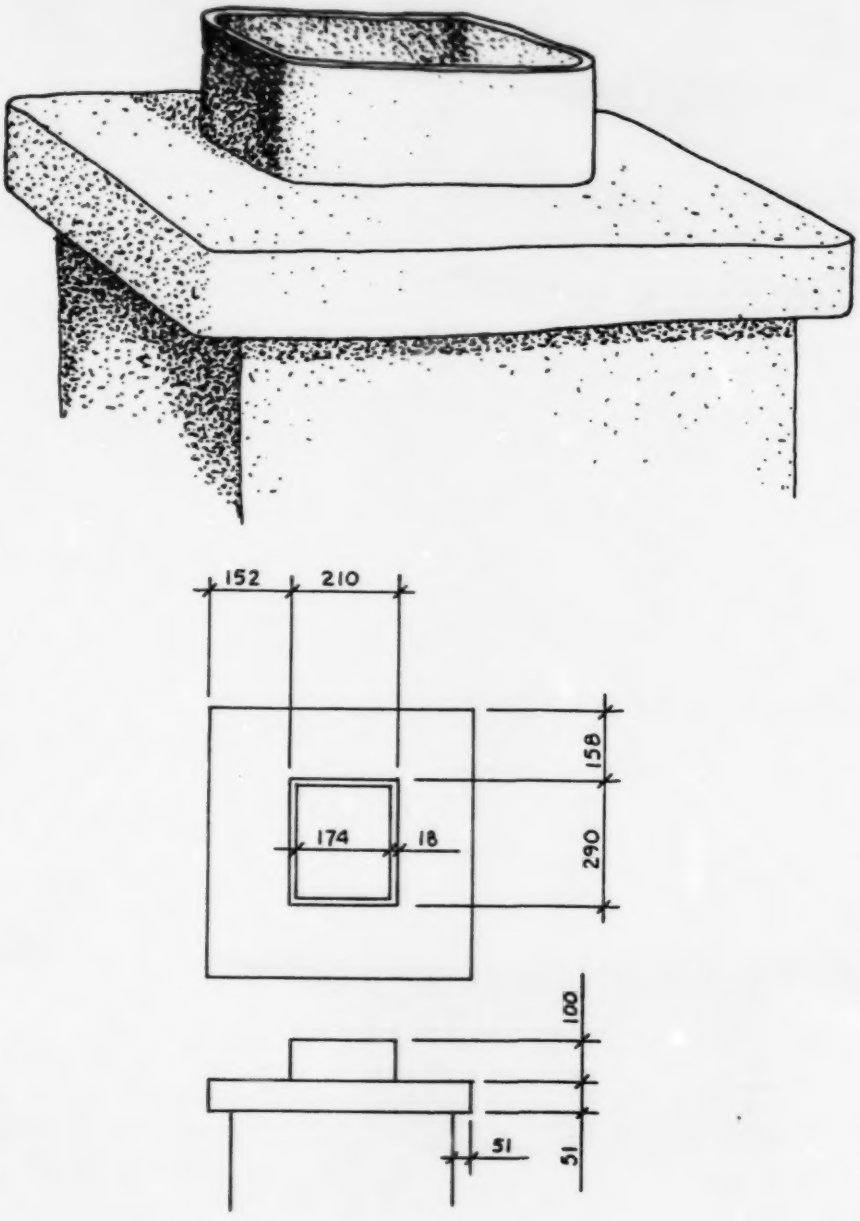

FIGURE B5: Masonry chimney with clay liner

APPENDIX C

ROWAN WILLIAMS DAVIES & IRWIN INC. REPORT
PERFORMANCE TESTING OF CHIMNEY FLUE CAPS

Rowan Williams
Davies & Irwin Inc.

Consulting Engineers
Microclimate Specialists

April 1, 1987

Mr. Michael Swinton
Scanada Consultants Limited
436 MacLaren Street
Ottawa, Ontario
K2P 0M8

Re: Performance Testing of Chimney Flue Caps

Dear Mr. Swinton:

As discussed in our recent telephone conversation, we are sending to you our results on the four types of chimney caps tested.

The tests were performed on four types of caps:

1. A vent, high temperature
2. B vent
3. Aero-cowl
4. Clay tile chimney

and where the clay tile chimney (4.) was tested with and without a chimney cap.

The tests were broken down into two types: 1) Natural Draft and ii) Induced Draft. Figure 1 shows a schematic representation of each while Figures 2 and 3 show photographs of the tested chimneys with their associated cap.

In the Natural Draft tests each chimney and its associated cap was placed in RWDI's boundary layer wind tunnel. The chimney was mounted so as to allow change in angle with respect to the floor which acted as a roof line, it was then joined via flexible duct to a pipe flow meter where measurements were taken to determine the volume flow rate up the chimney for the various angles tested. The approaching wind was parallel to the tunnel floor and was uniform, non-turbulent flow.

The results of these tests can be seen in Tables 1, 2 and 3. Table 1 is a listing of the ratios of the Draft Velocity (W) divided by the Windspeed (U). Table 2 shows the pressure coefficient values for the open flues at the W/U values given in Table 1. Table 3 shows pressure coefficients with the flues closed. These coefficients were calculated by measuring the static pressure in the chimney and dividing it by the dynamic pressure of the approaching wind. All coefficients were taken for the various angles and chimney configurations.

In the Induced Draft tests the chimney was connected to a variable speed blower, forcing air through the chimney and cap exhausting into the laboratory. These tests were performed with zero external wind speed.

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The results of these tests can be seen in Table 4, showing various volume flowrates with the corresponding velocity, chimney static pressure, and total pressure loss for the various configurations. Table 5 is a list of the cross sectional areas for the chimneys tested.

It can be seen from Table 2 and 3 that chimney 4 without cap produced the largest suction (negative coefficient). However, being open at the top, a down flow severly reduced the suction. The clay tile with cap performed very well because of the large size and bluff shape of the brick chimney which created a large acceleration over the top. The clay tile with cap performed well in both upflow and downflow conditions. In both upflow and downflow (negative and positive angle) the opening is situated in the wake of a bluff object. Chimney number 1 performed similarly. It too is fairly large, and like chimney 4 the opening is also protected by a wide deflector. In this case, the lower flashing produces a wake region in upflows.

Chimney 2 (B-vent) produced lower suctions because its smaller size created less local acceleration. However, performance was quite uniform over all angles since its opening too is protected on top and on bottom.

Chimney 3 produced the lowest suctions of all those tested. Its small size caused small accelerations for winds straight on. In upflows, it had its poorest performance. Since it had no large lower flashing, upward flowing winds were deflected over the opening by the baffle system. This acted to greatly reduce the suction on the opening.

In Table 4 it can be seen that the smaller caps were more restrictive.

In conclusion, it appears that larger diameter caps with protection from both above and below the opening are best in all situations.

If there are any questions regarding these results, we would be pleased to discuss them with you.

Yours very truly,

ROWAN WILLIAMS DAVIES & IRWIN Inc.

M. Accardo

Marco Accardo
Project Co-ordinator

Glenn D. Schuyler, P.Eng.
Principal

MA/jb
487-1314

TABLE 1

RATIOS OF W/U

CHIMNEY ANGLE	CHIMNEY 1	CHIMNEY 2	CHIMNEY 3	CHIMNEY 4 with cap	CHIMNEY 4 without cap
45 deg.	.053	.264	n/a	.041	.034
30 °	.226	.045	.020	.058	.048
0 °	.180	.064	n/a	.090	.076
-30 °	.074	.091	.028	.090	.058
-45 °	.142	.124	.034	.057	.048

TABLE 2

OPEN FLUE PRESSURE COEFFICIENTS

CHIMNEY ANGLE	CHIMNEY 1	CHIMNEY 2	CHIMNEY 3	CHIMNEY 4 with cap	CHIMNEY 4 without cap
45 deg.	-.216	-.274	-.239	-.583	-.263
30 °	-.531	-.248	-.235	-.753	-.755
0 °	-.500	-.269	-.229	-.669	-1.094
-30 °	-.395	-.218	-.166	-.759	-.837
-45 °	-.433	-.331	-.153	-.694	-.787

TABLE 3

CLOSED FLUE PRESSURE COEFFICIENTS

CHIMNEY ANGLE	CHIMNEY 1	CHIMNEY 2	CHIMNEY 3	CHIMNEY 4 with cap	CHIMNEY 4 without cap
45 deg.	-.662	-.432	-.461	-.792	-.242
30 °	-.731	-.446	-.621	-1.078	-.989
0 °	-.728	-.503	-.582	-.958	-1.626
-30 °	-.536	-.439	-.241	-.783	-.879
-45 °	-.556	-.648	-.136	-.729	-.818

TABLE 4

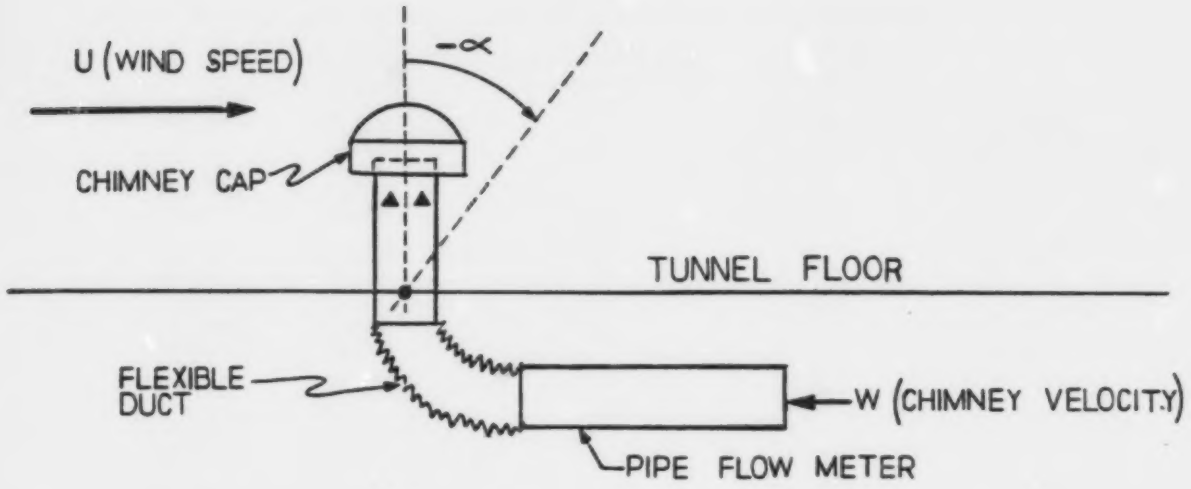
FLOWRATE VS CHIMNEY STATIC PRESSURE, VELOCITY AND TOTAL HEAD LOSS

	FLOWRATE (SLPS)	STATIC PRESSURE (Pascals)	VELOCITY (M/sec)	TOTAL HEAD LOSS (Pa.)
CHIMNEY 1	271.97	3	10.95	76.667
	265.59	3	10.69	73.217
	256.80	2	10.34	67.658
	240.32	2	9.68	59.512
	135.08	1	5.44	19.167
CHIMNEY 2	213.94	61	16.99	238.337
	210.24	62	16.59	239.344
	206.35	60	16.29	222.812
	189.29	52	14.94	188.983
	130.25	19	10.28	83.902
CHIMNEY 3	220.97	137	9.57	193.344
	198.44	130	8.59	175.471
	171.85	90	7.44	124.056
	133.19	51	5.77	71.444
CHIMNEY 4 WITH CAP	285.64	-1	6.50	24.917
	280.67	0	6.39	25.012
	279.75	1	6.36	26.067
CHIMNEY 4 WITHOUT CAP	287.88	-8	6.55	18.352
	254.93	-6	5.80	14.662
	251.38	-3	5.72	17.058

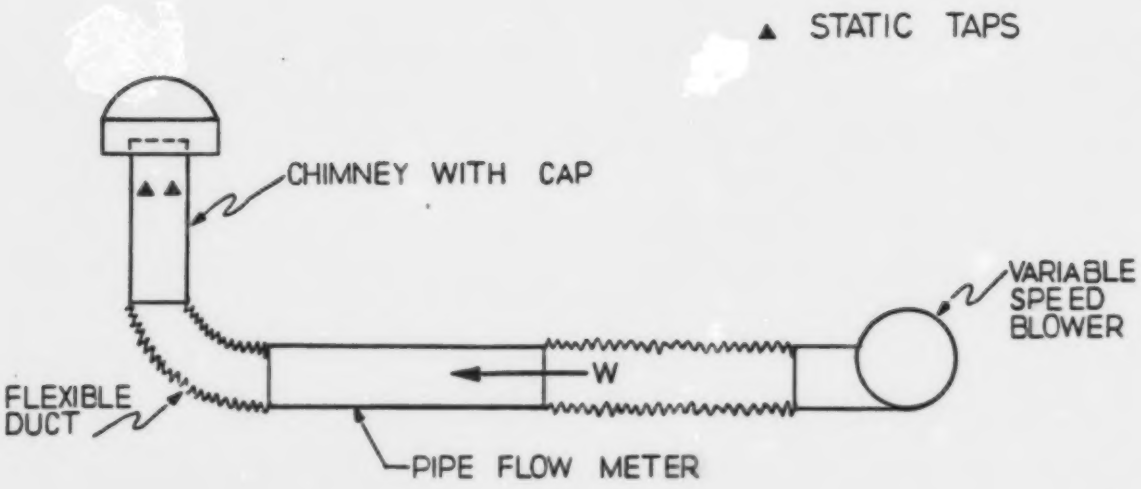
TABLE 5

SUMMARY OF CHIMNEY PROPERTIES

	AREA(M**2)	EXTERNAL DIMENSIONS
CHIMNEY 1- HIGH TEMPERATURE A-VENT	.0248	30.5 cm. dia.
CHIMNEY 2- B-VENT	.0127	13.8 cm. dia.
CHIMNEY 3- AERO-COWL	.0231	17.5 cm. dia.
CHIMNEY 4- CLAY TILE	.0439	42 cm. x 50 cm.

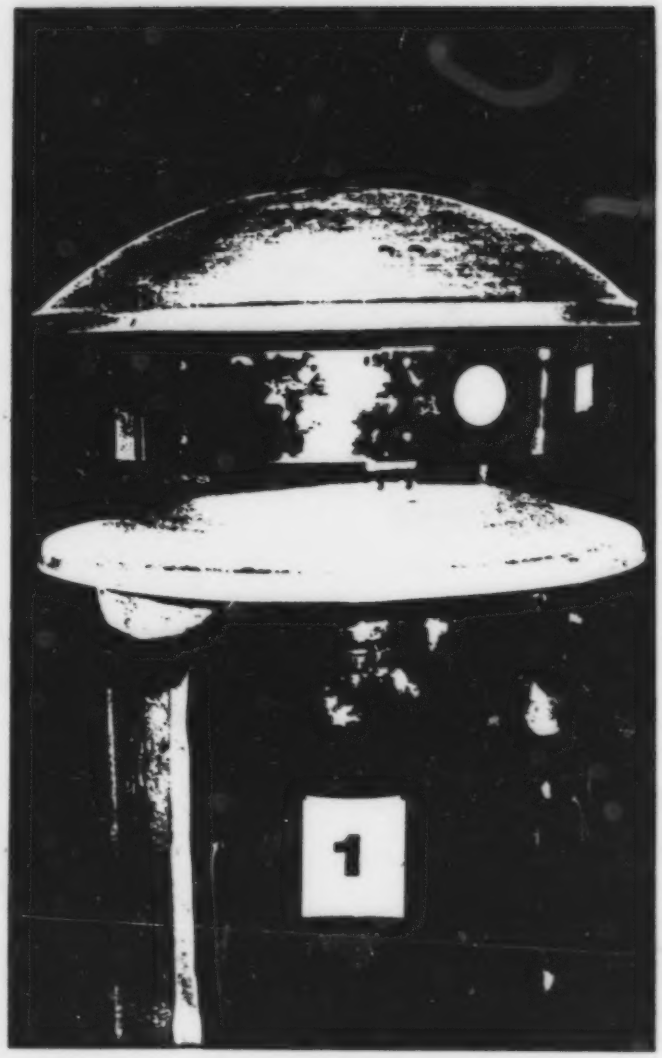


NATURAL DRAFT TEST SCHEMATIC



INDUCED DRAFT TEST SCHEMATIC

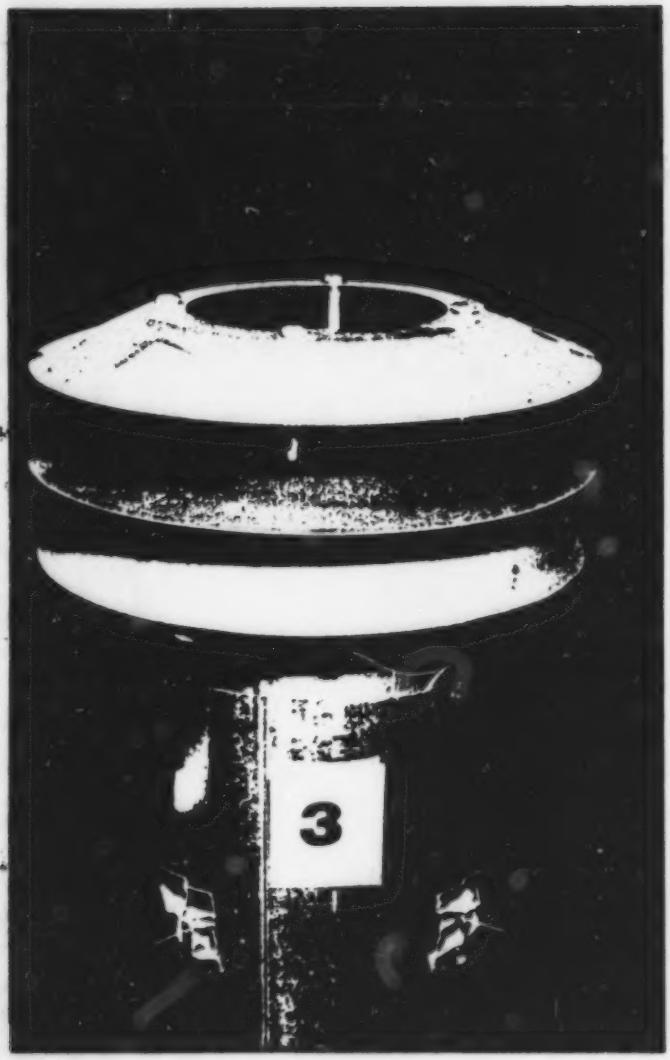
FIGURE 1



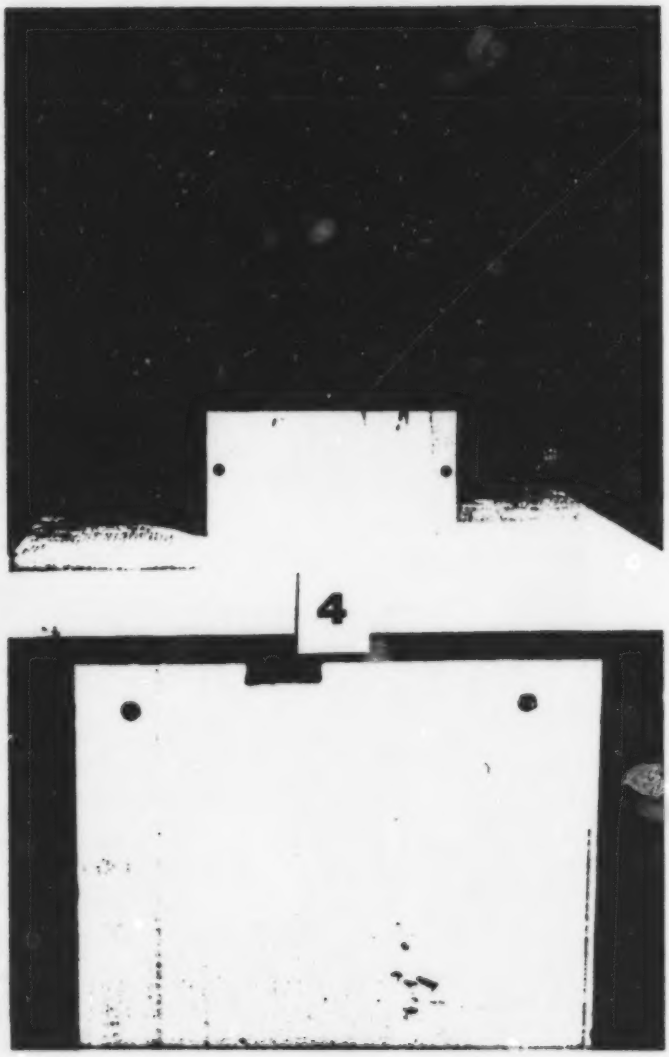
A – VENT

B – VENT

FIGURE 2
PHOTOGRAPHS OF TESTED CHIMNEY CAPS



AERO – COWL



CLAY TILE

FIGURE 3
PHOTOGRAPHS OF TESTED CHIMNEY CAPS

APPENDIX D

FURTHER ANALYSIS OF LABORATORY TEST RESULTS

FURTHER ANALYSIS OF LABORATORY TEST RESULTS

Although the laboratory test results are useful on their own, there remains a need for some means of minimizing the amount of data required as inputs in modelling the performance of flue termination configurations.

If the required data were available, one approach to modelling the effects of a flue cap would be to develop a matrix of tested wind pressure coefficients for all anticipated wind angles and flue flows that could reasonably be expected to occur. For example, the Flue Simulator model could be modified to interpolate between the entered performance values. This would allow the model to iteratively calculate a wind pressure coefficient that corresponds to the wind and flue flow conditions of the particular time step of a simulation. The model would also have to be modified to remove the existing friction factors for the termination configuration already in the model, since the measured wind pressure coefficient already accounts for friction effects as well as the aerodynamic wind effect.

Although the above approach would be rigorous in its accounting for cap performance, it is considered impractical. The user would be limited by the selection of caps already preprogrammed in the model or he would have to enter a large amount of data to model a special termination configuration. A means would have to be developed to efficiently store and allow editing of a potentially large amount of data. This approach was not considered realistic within the context of this limited study, but could be pursued in a more elaborate project.

The approach followed here was to hypothesize that some relationships could be developed between wind angle, flue flow and the

resulting wind pressure coefficient, and that these relationships could be used generally in modelling. As described under ANALYSIS OF THE TEST RESULTS in the main report, the assumed relationship between wind angle and total wind pressure coefficient for a blocked flue is:

$$C_t = C_h \cdot COS0^2 + C_v . SIN0^2$$

where:

C_h is the wind pressure coefficient measured at 0° angle of attack

0 is the angle of attack of the wind measured from the horizontal

h,v and t are subscripts indicating horizontal, total and vertical components

A trial-and-error approach was used to develop the best combinations of C_h, and C_v that fit the test data for all wind angles of attack. Initial attempts at fitting the data were not good. It was realized that all the caps appeared to turn the wind locally (although no flow visualization was done to support this presumption) and that a phase shift had to be added to the wind angle to better fit the data. The resulting values that best fit the data are shown below.

	PHASE SHIFT	C_h	C_v
A-VENT	20°	0.77	0.4
B-VENT	10°	0.52	0.3
Aerocowl	20°	0.63	0.0
OPEN MASONRY CHIMNEY	0°	1.63	1.0
CAP & GRILL	30°	1.08	0.7

The results of each fit are shown graphically in Figures D1 to D5. Most fits are reasonably good at low angles of attack, although no combination was found that properly fit the open masonry flue for both positive and negative angles of attack. In the latter case, there seems to be excessive lift at 0°, presumably caused by airfoil shaped steamlines over the flue exit. This effect seems to disappear at small deviations from horizontal.

Deviations between fitted and measured points indicate the cases for which the hypothesis of constant component wind pressure coefficients did not hold true. It does appear to hold true for all caps over limited ranges of wind angle and for some caps (e.g. the Aerocowl, Figure D3) over wider ranges of wind angle.

The phase shift is interpreted in the following way: When the wind is perfectly horizontal, the A-vent "sees" it as an updrafting wind of 20°, and the B-vent sees it as a 10° updraft. This means that the tested caps apparently straighten downdrafting winds into more horizontal direction - a desirable feature in preventing backdraft. The open masonry chimney had no apparent phase shift.

Also of interest in the table are the extremes in the deduced vertical wind pressure coefficient. The value of 1 for the open masonry chimney implies that the entire downdrafting component of wind is converted to downward dynamic pressure, as would be expected since their is nothing to resist this. The other vertical wind pressure coefficient of interest is that of the Aerocowl. The value of 0 suggests that this design completely eliminates the vertical effects of wind for both the positive and negative angles of attack tested. This is likely due to the 3 sharp-edged fins that are a feature of this design.

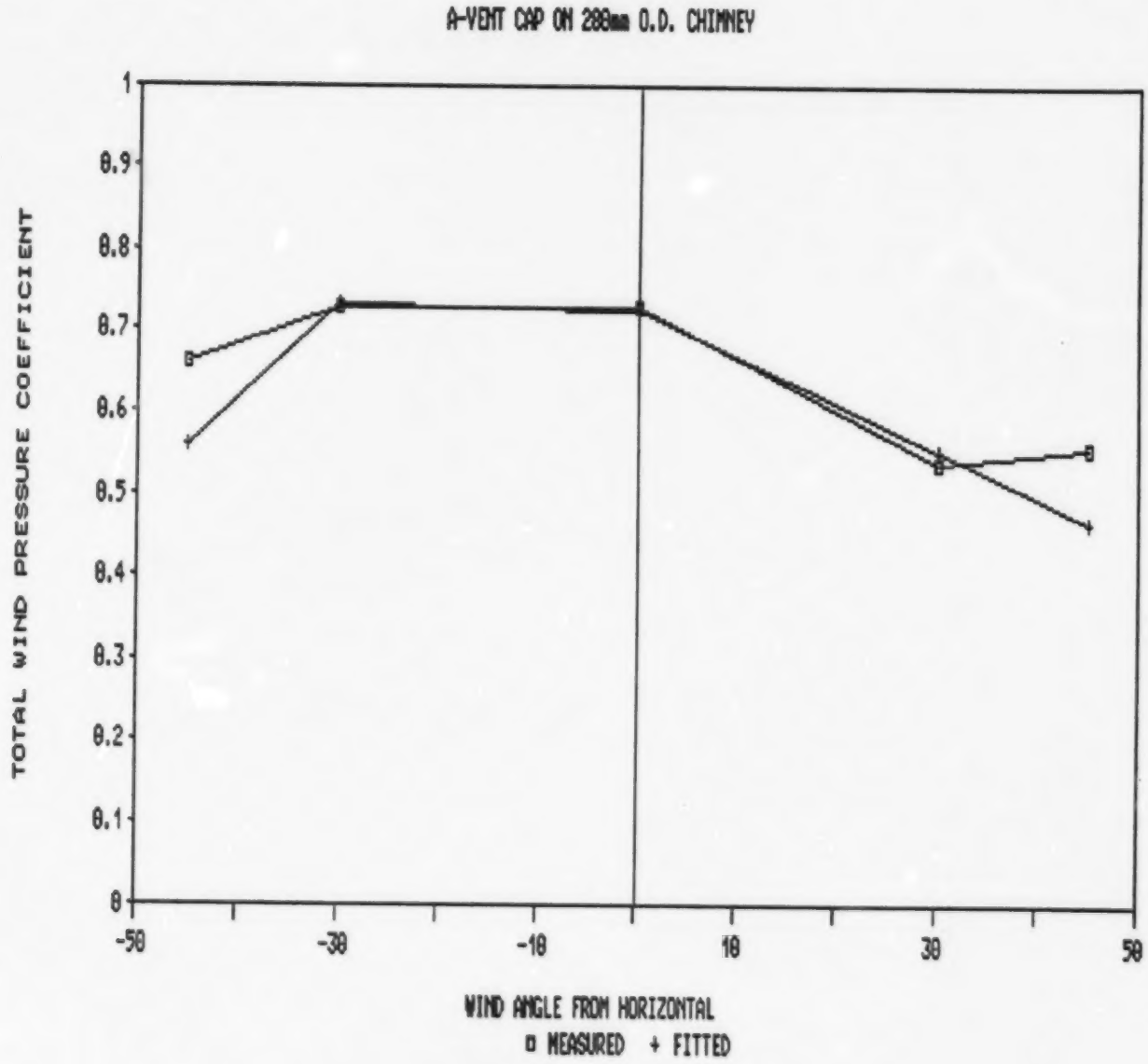


FIGURE D1: **Measured and curve fitted total wind pressure coefficients of the A-vent.**

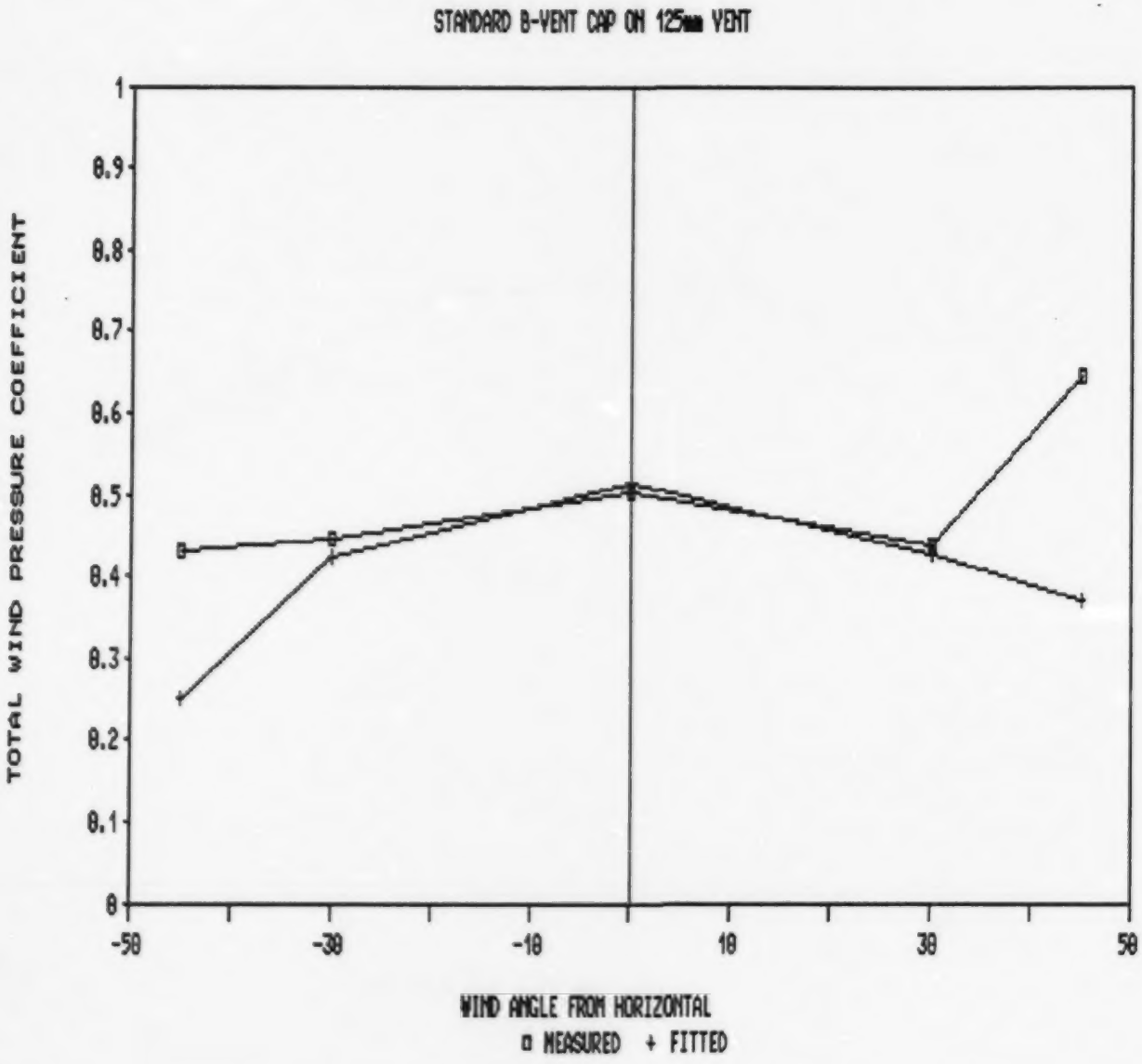


FIGURE D2: **Measured and curve fitted total wind pressure coefficients of the B-vent.**

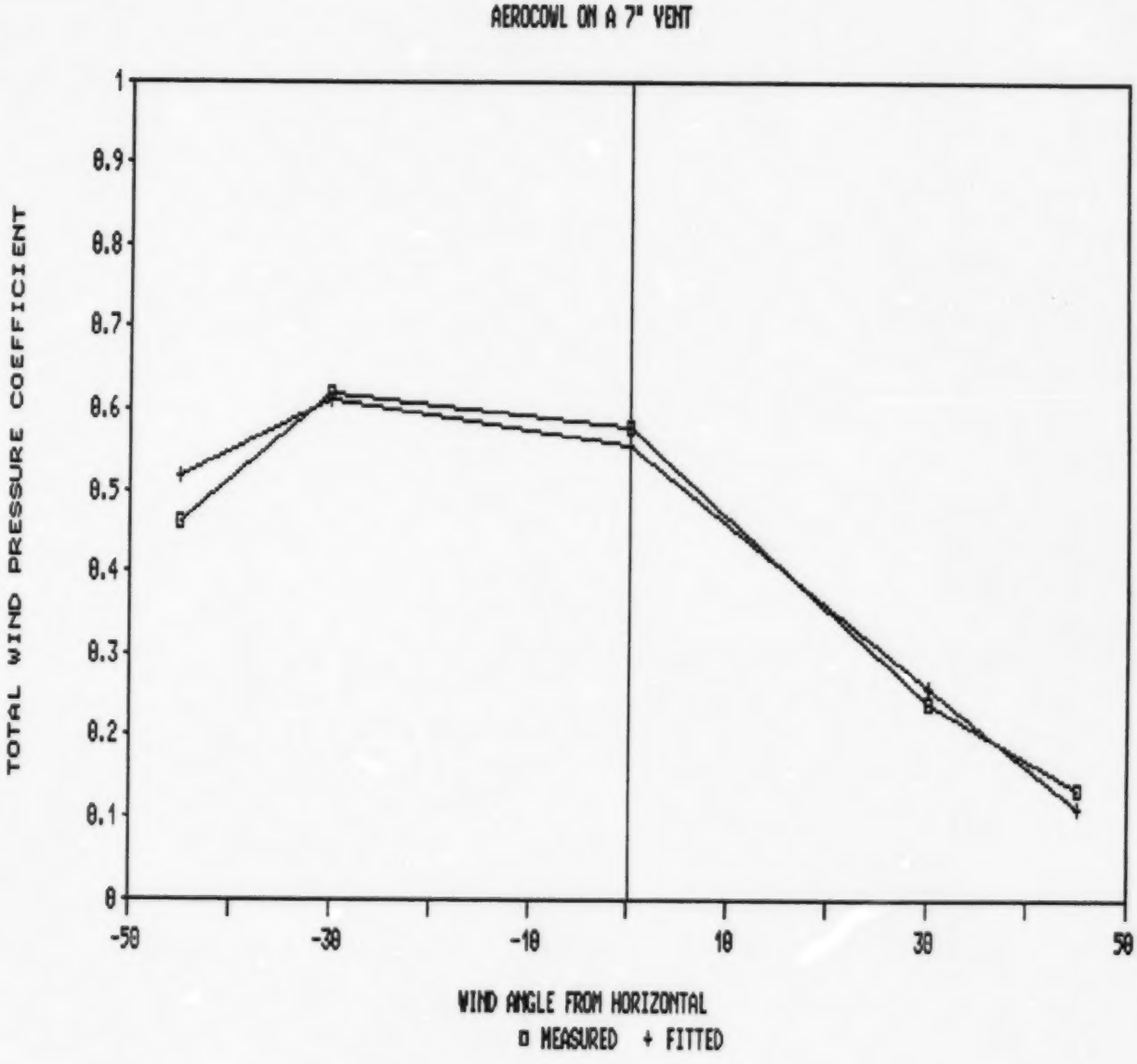


FIGURE D3: **Measured and curve fitted total wind pressure coefficients of the aerocowl.**

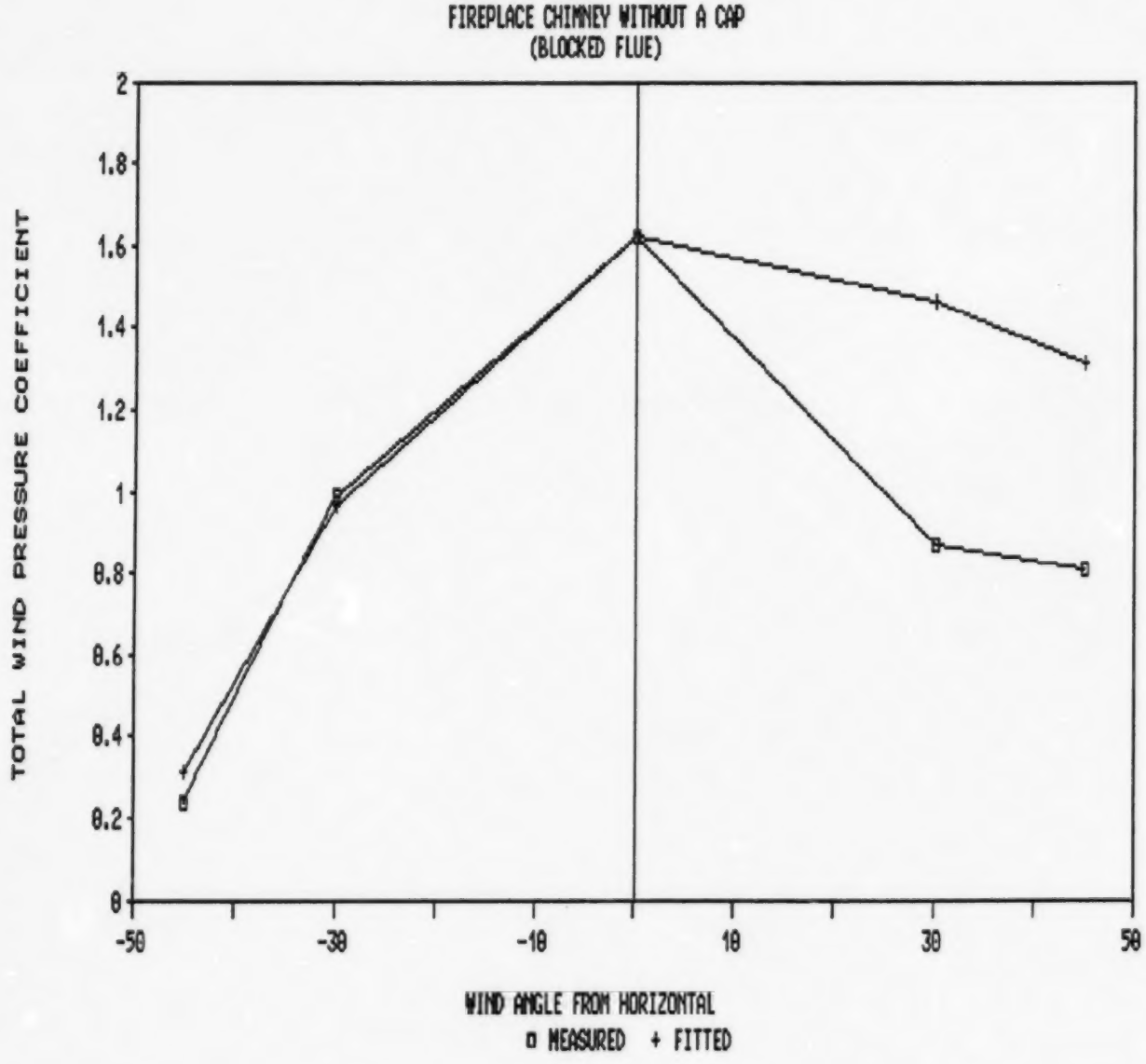


FIGURE D4: **Measured and curve fitted total wind pressure coefficients of the open masonry chimney.**

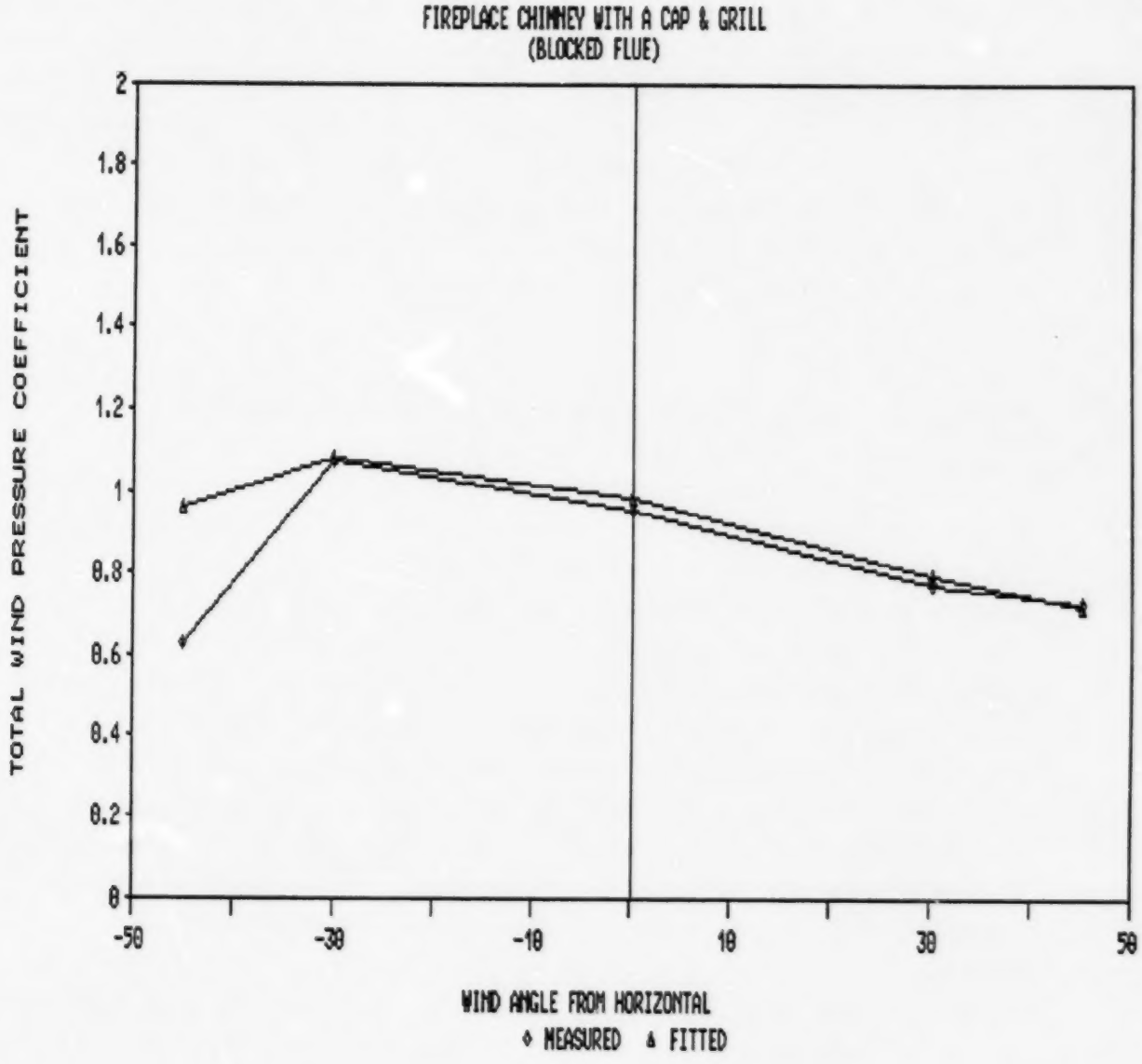


FIGURE D5: **Measured and curve fitted total wind pressure coefficients of the masonry chimney with cap and grill.**

Use in the FLUE SIMULATOR Model

In spite of the moderate success of the curve fitting exercise in highlighting the differences in performance of the various flue termination configurations, the curve fits were not considered good enough in all cases and angles to use this technique in the model. As the real performance of the caps is of interest, it was decided to allow the user to input total wind pressure coefficients obtained directly from test data such as that produced by RWDI, or as found in Reference 1.

Effect of Flue Flow on the Wind Pressure Coefficient

The wind pressure coefficient is derived from a static pressure measurement inside and at the top of the flue. That pressure is relative to ambient. This measurement is difficult to relate to an analytical formulation of pressure and flow, such as the Bernoulli equation, for two reasons. First, the Bernoulli equation does not allow for the inclusion of an aerodynamically induced pressure drop within the stream due to the action of another stream (i.e. the wind). Second, the measured static pressure difference across the flue termination device is due to two factors - aerodynamic and friction effects. The friction effects make the flue pressure higher than ambient; the aerodynamic effects can make the flue pressure go either way, depending on wind angle of attack and design of the device. Since the aerodynamic effect is not in the Bernoulli equation and it cannot be separated out of the wind pressure coefficient, difficulties arise in formulating a model of the effect of the cap.

A hypothesis was developed based on two considerations. **First,** measurement of the wind pressure coefficient of a blocked flue provides a pure aerodynamic wind effect term that can be added into the Bernoulli equation. That measurement is pure since there is no friction loss due to flue flow in a blocked flue. This term can be derived from the first set of measurements made by RWDI - it is simply the wind pressure coefficient multiplied by the dynamic head of the wind. **Second,** a pure measurement of friction drop across the flue termination device in the absence of wind yields a friction factor that is independent of wind action. The friction term was derived from the third series of RWDI tests - it is the friction factor multiplied by the dynamic head of the flue flow.

The hypothesis is that the aerodynamic and friction effects in the flue termination device are independent.

This hypothesis can be tested on the results of the first and second series of RWDI tests - the measurements of wind pressure coefficients with the flues blocked and unblocked. If it were true that the aerodynamic effect and the friction effect were independent, then the change in static pressure in the flue that occurs when the flue is unblocked would be entirely due to friction effects of the flow through the termination device. That is, if the aerodynamic effect is constant for all flue flows then the only explanation for the difference in pressure that occurs across the flue termination device when the flue is unblocked is that this difference is due to the friction effect.

Using the wind pressure coefficient derived for the blocked flue conditions and the friction factor derived from the pressure/flow, no wind tests, one can plot the change in static pressure in the flue resulting from unblocking the flue versus

the pressure difference across the termination device due to friction resulting from the flue flow (the termination device friction pressure drop). (The flue flow velocities were calculated using the velocity ratios reported in the wind pressure coefficient tests with the unblocked flues.) This was done for all termination configurations. The results are shown in Figure D6.

The plot shows no systematic relationship between the change in static pressure in the flue and the termination device friction pressure drop. Moreover, the friction pressure drop is an order of magnitude lower than the actual change in flue static pressure, which indicates that the friction term could contribute in only a limited way to the change in static pressure in the flue.

This finding has two implications. First, the measured change in flue static pressure during combined wind and flue flow conditions, when non-dimensionalized, can properly be termed "wind pressure coefficient" since the effect being measured is apparently due to an aerodynamic effect not a discharge loss effect. (This would not hold for very low winds on flue caps that are very restrictive, so that interpretation of laboratory measurements under such conditions would have to be done cautiously). Second, because the discharge loss is relatively small for all but the lowest wind speeds and most constricting caps, the aerodynamic effect can be thought of as acting **outside** the termination device, even though the measurement is traditionally taken inside the flue. This allows us to treat friction pressure drop in **series** with the aerodynamic effect and therefore independently. We can therefore get around the limited Bernoulli equation ny using the wind pressure coefficient to calculate an

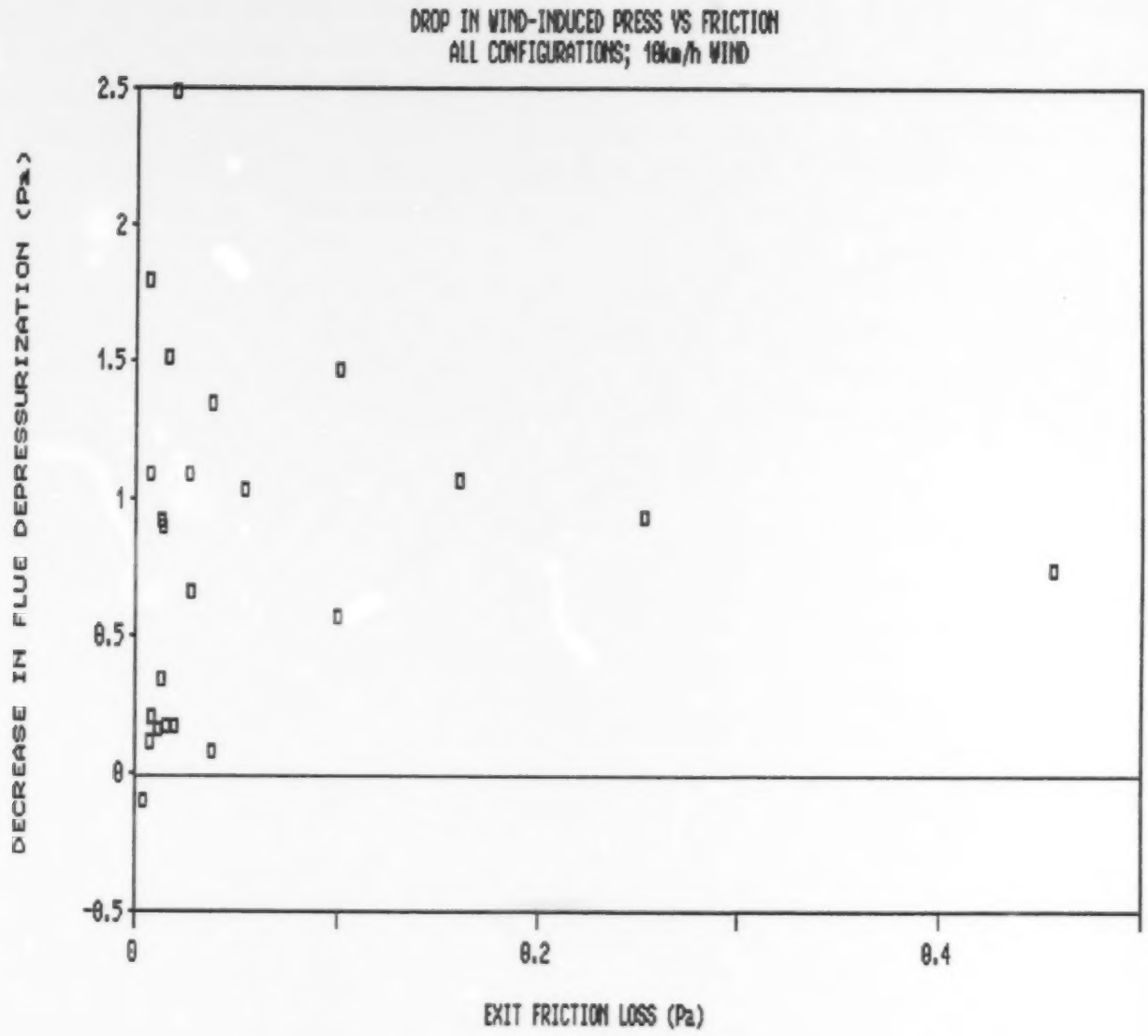


FIGURE D6: Drop in wind-induced pressure vs friction due to flue flow.

effective ambient pressure outside the flue termination. Since the wind pressure coefficient already incorporates the termination device friction pressure drop, this approach is only an approximation which double counts the friction pressure drop. However, in the absence of comprehensive test data, it must be used to allow the modelling of a wide range of combinations of wind and flue flow. (e.g. The combination of no wind and high flue flow would not be modelled very well if only the wind pressure coefficient were used.) It is the approach used in the FLUE SIMULATOR model.

However, because of the failure of the hypothesis, no analytical means is currently available to dynamically link change in wind pressure coefficient and flue flow velocity.